A STUDY OF THE EFFECTS OF STRESS RATIO AND LOW TEMPERATURE ON THE FAILURE OF MILD STEEL CYLINDERS

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List of Symbols

σ_a -----Nominal axial stress, psi

σ_t -----Nominal tangential stress, psi

σ_r -----Nominal radial stress, psi

$\bar{\sigma}_a$ -----True axial stress, psi

$\bar{\sigma}_t$ -----True tangential stress, psi

$\bar{\sigma}_r$ -----True radial stfess, psi

$\bar{\tau}_n$ -----Octahedral shear stress, psi

n -----Nominal stress ratio at failure, $\frac{\sigma_a}{\sigma_t}$

$\bar{n}$ -----True stress ratio at failure, $\frac{\bar{\sigma}_a}{\bar{\sigma}_t}$

t -----wall thickness, inches

L -----gage length, inches

A -----Cross sectional area, square inches

I.D. -----Inside diameter, inches

O.D. -----Outside diameter, inches

P ----- Tension, pounds

p -----Hydraulic Load, pounds

SUMMARY

This report covers the results of 35 tests of cylindrical mild steel specimens under conditions of varying biaxial stress ratio and temperature. Behavior of test specimens is reported in the form of per cent elongation, per cent reduction in area, true and nominal fracture stresses, type of fracture, and temperature at fracture. Fracture data are plotted to permit derivation of the failure curve for the specimens tested under conditions of varying stress ratio and temperature.

INTRODUCTION

On the basis of the procedures and results outlined in reference (1), this thesis was originally intended to develop the exact conditions of biaxial stress and temperature under which the normally ductile behavior of mild steel became brittle. i.e., the steel showed abnormally low per cent elongation and failure stresses, and failed by the distinctive cleavage fracture. It was hoped thereby to develop information as to the brittle behavior of ship's steel under conditions of stress approximating those found in welded ship's structures.

Test procedure was arranged to permit taking data on the three criteria of brittle behavior: ductility (per cent elongation), stresses at failure, and type of fracture. Failure temperature, of course, was included in data taken.

It was further desired to verify the validity of the extension of the Hencky-von Mises theory of yielding to the failure of cylindrical specimens under conditions of biaxial stress, as mentioned in references (1) and (5).

The first low temperature tests indicated that, as was suspected from research, brittle behavior of the specimens was not to be attained at the temperatures attainable by use of solid CO_2. It was therefore decided to continue testing at low temperatures in order 1) to ascertain the effect of temperature on the behavior of the specimens, 2) to develop, if possible, a means of predicting the failure of mild steel under conditions of biaxial stress.

Procedure

The procedure outlined in reference (1) was followed except as modified below.

The specimens obtained were 2.875 inch outside diameter, nominal 0.120 inch wall thickness mild steel seamless tubes 18 inches in length.

The specimens were annealed prior to machining by heating to 1650°F and held at that temperature for thirty minutes. Since the annealing furnace was not long enough to accomodate the entire specimen, the specimen was then reversed and the same procedure as outlined above followed. The specimen was then allowed to cool in the furnace. To avoid rapid cooling of the end protruding from the furnace, an asbestos filled box was made to enclose this portion of the pipe and in effect, extend the length of the furnace. Pipes number 24, 33, 36, and 37 were not annealed. The annealing process forms a hard, black scale on the specimen. Machining is facilitated if this scale is chipped off prior to placing the specimen in the lathe.

The specimen was then placed in the lathe using either a three jaw or four jaw chuck and aligned. A three or four inch section was then machined five inches from the free end of the pipe to form a surface for a steady rest.

After securing the steady rest, the specimen was bored over the middle five inch length until a smooth, round surface was obtained. The depth of cut was noted so that it would be possible to obtain any desired wall thickness in the test section.

The steady rest was then removed and the outside of the specimen machined as shown in plate 52 . It was found that support was not

needed at the free end of the specimen if light cuts (0.010" and below) were used. Due to the limited capacity of the hydraulic pump of the test apparatus, the wall thickness of specimens was varied with the stress ratio desired. The wall thickness varied from 0.050" to 0.100".

After machining, the specimens were marked with two gage lengths two inches long on opposite sides of the test section. The pipe was then measured to determine the outside diameter and wall thickness of the four inch test section. Six readings were made to determine the outside diameter: at each end and at the center of the four inch test section in planes 90 degrees apart. Twelve readings were made to determine the wall thickness: at each end and at the center of the test section in four locations spaced 90 degrees around the pipe.

The latter measurements were made on a special micrometer built for this purpose and shown diagramatically in plate 51. The test circuit is to insure that the specimen's inner wall is contacting the center contact of the micrometer arm. The feeler completes the circuit when the switch is in the test position.

The average outside diameter and wall thickness are used to obtain the average inside diameter of the test section.

To decrease the time lag between tests, an additional set of plugs, wedges, and pressure cups was made. The second set of plugs was made slightly larger in diameter than the original set since the variation of inside diameter of the specimens was too wide to allow a tight fit using the original plugs.

Plugs were forced into the specimens using the Tinius-Olsen tensile machine. This was done to make possible the assembly of one specimen while another was in the Baldwin-Emery machine being cooled.

Before the specimen was mounted in the Baldwin-Emery machine, the collars were turned tight. This procedure is much easier than turning the collars tight after the specimen is in the tensile machine.

Strain gages were not used in this investigation since we were concerned with the conditions at failure of the specimens.

The refrigeration system was altered to reduce the length of ducting in an attempt to reach lower temperatures than those obtained with the original system. Towards this end, the specimen box was mounted directly to the outlet flange of the refrigerator box. The remaining ducting and the specimen box were wrapped with rock wool batting and a canvas covering. A baffle was fitted in each half of the specimen box to reduce the air space in the box. To obtain the lowest temperatures (-40°F and below) dry ice was placed in the specimen box after surrounding the specimen with wide mesh wire screen to prevent direct contact between the dry ice and the specimen.

The capacity of the reservoir on the hydraulic pump was increased by fastening a one quart can to the filling hole on the pump reservoir. It was then unnecessary to refill the pump during the conduct of a test.

Results

1. Plates 1 through 34, Appendix I, set forth the data concerning the original dimensions, fracture conditions and final dimensions of each specimen tested. Tests 8 and 24 were unsuccessful: the former because of the failure of a collar, the latter because after axial failure had occurred the tensile machine was inadvertantly left on, and a second, circumferential, failure resulted, thus invalidating test results. True fracture stresses were determined after testing by measuring the outside diameter and wall thickness of the specimen and using these dimensions and tensile and pressure load at failure, calculating σ_a, σ_t, and σ_r.

2. Plates 35 through 38, Appendix I, set forth the comparative data for each specimen tested, excluding tests 8 and 24. The data is arranged, it will be noted, according to stress ratio in order of decreasing failure temperature.

3. Plate 39, Appendix II, is a plot of true fracture stresses for each test completed. Data from the reports of other experimenters are included , as noted on the plot. The broken line was derived from the average of fracture stresses at $\bar{n} =$ 1, 2, 3, and 4, excluding data from test 5 and the other experimenters. The solid line was derived from the average of fracture stresses at $\bar{n} =$ 1, 2, 3, and 4, excluding stresses for those specimens whose inside finish was not either "smooth" or "fairly smooth".

4. Plate 40, Appendix II, is a plot of true octahedral shear stress at failure, including data from other experimenters. The broken line was derived by averaging τ_n's for $\bar{n} =$ 1, 2, 3, and 4,

excluding the data taken from the results of other researchers. The solid line was similarly derived, except that only data from specimens whose inside finish was "smooth" or "fairly smooth" were used.

5. Plate 41 shows the spots of plot 40 with symbols added to describe the inner finish of specimens noted in plates 35 through 38 as inferior to "fairly smooth".

6. Plates 42 through 47, Appendix II, are plots of true fracture stresses according to failure temperatures, upon which has been superimposed the solid line of plate 39, derived as indicated in paragraph 3 above.

7. Plate 48, Appendix II, combines three plots. The first of these is the solid line of plate 39 extended to the vertical axis, then reflected to cover that part of the plot between $\bar{n} = 0$ and $\bar{n} = 1$. The second line (broken) is the Hencky-Von Mises parabola for $\bar{\tau}_n = 40{,}000$psi, and the third line, also broken, is a circular arc whose equation is $\sqrt{\bar{\sigma}_a^2 + \bar{\sigma}_t^2} = 105{,}000$ psi.

8. Plate 49, Appendix II, is the solid line of plate 40, upon which has been supermiposed the straight line $\bar{\tau}_n = 40{,}000$ psi and the curved line corresponding to the circular arc $\sqrt{\bar{\sigma}_a^2 + \bar{\sigma}_t^2} = 105{,}000$ psi in plate 48.

Discussion of Results

1. Plates 39 and 40 show plots of all tests conducted, together with results taken from the reports of other researchers. It will be noted that though the spots show a pronounced scatter, those which have been calculated from test results do not show more scatter than those taken from the literature. The scatter of points can be attributed to several factors: the discussion that follows will elaborate on possible causes of the variation in failure stresses.

The condition of restraint of the test section is a possible cause of varying results. Should the specimen be mounted eccentrically in the tensile machine, bending of the specimen would result. Such a condition was possible in this series of tests since the test section was not always perfectly concentric with the ends of the specimen because of its not being perfectly round as received.

Another possible cause of bending is variation in wall thickness around the circumference of the specimen. Such a variation would result in a non-uniform stress distribution and consequently bending of the specimen.

That there was in fact little bending in the specimens is indicated by the fact that in no case did after-fracture measurements of gage marks on opposite sides of the test section differ appreciably. It is therefore concluded that there was insufficient bending in test specimens to affect failure stresses materially.

Stress concentrations resulting from abrupt changes in wall thickness can very definitely affect specimen behavior. In machining the specimens, an attempt was made to provide a transition wherever there was a change in wall thickness. In eight tests (1, 5, 7, 12, 13, 22, 25, and 30) the specimen failed within one-quarter inch of a test section end. One might at first glance conclude that these failures

were the result of a stress concentration at the end of the test section. Close inspection of the initial dimensions of the test section of each specimen, however, revealed that in every case the location of the fracture was at the point of minimum wall thickness. In test number 7 there was a definite tool mark on the inner surface of the test section. It is felt that this discontinuity caused the 55% cleavage fracture which occurred, apparently the only failure which resulted from a stress concentration.

Another variable in testing was the surface finish of the specimens. In general the outer surfaces of the test sections were finished smooth, and showed little variation from specimen to specimen. The inner surfaces of the test sections, however, showed marked differences in finish, in spite of careful machining. The inner surface of each specimen had to be bored in order to insure a uniform wall thickness, but as a consequence of the shape of the tubing, the "blind" nature of the operation, and the limitations of the equipment available, it was impossible to insure a smooth inside finish in many cases. Lack of internal grinding equipment made it difficult to eliminate the tool chatter marks which frequently resulted from the light finishing cuts, and in any case it was extremely difficult to eliminate tool chatter once it began.

As will be noted on plates 35 through 38, 14 specimens have internal surfaces rated worse than "fairly smooth". Of these 14, only four points fall above the average of all test points on pages 39 and 40. This would indicate that the finish of a specimen as a first-order effect on its strength. For this reason two curves are shown on plates 39 and 40. The dashed curve is the average of all test points,

whereas the solid curve is the average of all specimens having a "fairly smooth" or "smooth" inner surface. On plate 40 both curves show the same trend, a fact which shows that even the rough specimens fail at progressively higher octrahedral shear stresses as $\bar{n}$ increases. It is felt that the solid curve is the more accurate representation of the failure of cylindrical specimens of mild steel under the conditions of these tests.

The temperature of failure seems to have little or no effect on the failure of the specimens tested, either as regards per cent elongation or failure stresses. This is evidently the result of the fact that the minimum temperature attainable with the refrigeration system operating with solid CO_2 is much above the transition temperature for mild steel tested under conditions of biaxial stress. The transition temperature for any testing procedure, of course, is a function of that procedure as well as the properties of the material tested.

It should be mentioned that the temperature of the specimen was changing continuously during the test period, the change in temperature from beginning to end of a test being in the neighborhood of ten degrees F. This was the result of the pumping of hydraulic oil at atmospheric temperature into the specimen to maintain pressure as the specimen yielded under test stresses. It was necessary under these conditions to begin a test with the specimen at a temperature ten degrees below that desired at failure. It is believed that this temperature change had no effect beyond that of causing some difficulty in predicting exact failure temperature as may be noted in plates 35 through 38.

No variation in failure stresses results from varying wall thickness, as may be seen from plates 35 through 38. E. A. Davis, in reference (6) reports that there is no apparent size effect in his tests of specimens

of a type similar to that used in these tests.

Only four specimens were not annealed in this series. Two of the specimens failed at stresses above the average of all tests and the remaining two failed below this average. Although insufficient tests were performed to allow a definite statement on the matter, the results of these four tests, together with those reported in reference (5), of which there were five, indicate that annealing does not greatly improve the failure properties of mild steel when tested under conditions of biaxial stress and low temperature. As noted in reference (4) any residual stresses present in the specimen at the beginning of a test are relieved by plastic flow long before failure occurs; since the main result of annealing, according to the same source, is, in the case of unwelded steel, stress relief, it is to be expected that unannealed specimens would behave substantially the same as those which had been annealed.

A final factor remains which materially affects failure stresses· that of differences in the steel of the specimens. During the process of machining, hard spots were often encountered in the walls of the tubing. These hard spots were an indication of non-uniformity in the specimens; it is rather unlikely that specimens, machined from unselected, run-of-the-mill seamless steel tubing, would be uniform in either chemical composition or microstructure. For this reason it is felt that the differences of the specimens as regards structure and composition exercised a strong influence on failure stresses, and it is regretted that time did not permit a study of tested specimens from the point of view of their microstructure.

It is not easy to pinpoint the exact reasons for the scatter in test results. but from the discussion above it appears that the primary reasons for this difference must be 1) the differences of individual specimens in

structure and composition and 2) the quality of the finish of the inner surface of the test section of each specimen. The other factors mentioned above seem to have had a second-order effect if any at all on the behavior of specimens. All things considered, it is most encouraging that test results compared as well as they did with those attained by others who had more elaborate facilities at their disposal.

2. Three cleavage fractures were obtained. Test number 7, as noted above, showed a 55% cleavage fracture, which was apparently the result of a tool mark which measured 0.008" deep after failure. This tool mark constituted a stress raiser which, combined with the low temperature at failure, led to the distinctive cleavage fracture. The specimen in test number 22 failed with 60% cleavage. In this case there is no evidence of a tool mark, though the inner surface is noted as "rough". Probably the cleavage fracture is the result of three factors acting together: The chemical composition and microstructure of the material of the specimen, its inner finish, and the rapidity with which the rupture propagated once it was initiated. The fact that the specimen was not annealed is not considered significant in the light of the behavior of the three remaining unannealed specimens. It should be noted that test number 16, conducted under like conditions of $\bar{n}$ and temperature, ended in shear failure; the inner finish in this case is noted as "fairly smooth". The same reasoning may be applied to the 5% cleavage fracture of test number 6 as set forth for test 22: The specimen of test number 6 had a "fairly rough" inner surface.

It is significant that all three specimens which failed with cleavage fracture showed no appreciable reduction in either per cent elongation, or failure stresses; test 6 and 22 had failure stresses

above the average, while the specimen in test 7 failed at stresses somewhat below the average. This illustrates the well-known fact that a material such as steel may fail in a mannner characteristic of brittle substances (cleavage fracture) while exhibiting normal ductile behavior prior to failure.

3. It will be noted that true stresses at failure are used in plotting the spots of plates 39 and 40. These stresses, computed as noted above in the Results Section, are commonly used as being the most accurate representation of the behavior of the specimen at the moment of rupture. As an inspection of plate 40 will show, the true octahedral shear stress plot affords the clearest picture of the behavior of test specimens as $\bar{n}$ increases, and therefore, is the most significant plot. On both plates 39 and 40, the curves passed through the average failure stresses are not extended beyond the stress ratios actually covered by these tests. Above the stress ratio of 4.5, of course, there is no information available so far as the authors have been able to ascertain. It is reasonable to suspect, however, that there is an inflection point in the curve of $\bar{\tau}_n$ in the vicinity of $\bar{n} = 4.5$. For stress ratios of less than 0.90 there are data available, but points are so few and scattered as to make plotting of the line of failure impossible. It is for this reason that plate 40 has been plotted on a scale which allows so little space between the $\bar{n} = 0$ and $\bar{n} = 1$ abscissae. From the points plotted on plate 39 at stress ratios near zero, however, it seems apparent that the steel is anisotropic, for the few points that are available show a marked reduction in the largest fracture stress when $\bar{\sigma}_t$ is larger than $\bar{\sigma}_a$. The line of failure, therefore, in the range $0 \leq \bar{n} \leq 1$ should greatly differ from that in the range of testing $1 \leq \bar{n} \leq 4.5$. Confirmation of this

conclusion, of course, awaits further testing.

Plate 40 clearly indicates that the Hencky-Von Mises (constant octahedral shear stress) theory of failure does not predict the behavior of specimens at true stress ratios above about 2.0 Plate 39 indicates that the maximum normal stress criterion also fails to predict failure. References (1) and (5), on the basis of more limited testing, advanced the Hencky-Von Mises theory as adequately predicting the failure of specimens of this type under conditions of biaxial stress.

4. Plate 48 is plotted on the assumption that mild steel behaves isotropically. This assumption is subject to serious doubt as noted above; therefore the curves of plate 48 are presented as a matter of interest only. It will be noted that the Hencky-Von Mises parabola does not conform at all closely to the curve extrapolated from experimental data. This situation is not unexpected from the plot of plate 39, of course. The circular arc, on the other hand, closely approximates the experimental curve; it may well be the curve of failure for steel tested as in this thesis, though only further testing will positively demonstrate this hypothesis. Certainly the circular arc shows good agreement in the area covered by testing.

Plate 49 embodies the plots of $\bar{\tau}_n$ and $\bar{n}$ which correspond to those of $\bar{\sigma}_a$ and $\bar{\sigma}_t$ in plate 48. The same trends are shown as in plate 48. It should be noted that the experimental curve of this plate is not the same as that in plate 40; it is believed that this difference is due to the fact that $\bar{\tau}_n$ is calculated from a quadratic equation while $\bar{\sigma}_a$ and $\bar{\sigma}_t$ are taken directly from test data. The difference in any case is less than 4%.

CONCLUSIONS

1. Insofar as the mild steel cylindrical specimen reproduces the stress distribution present in elements of a ship's structure, results of these tests indicate that a combination of biaxial stress and low temperature-down to a temperature of -50°F-will not by itself result in brittle behavior.

2. In the temperature range 0° to -50° F, temperature by itself has no discernible effect on failure stresses, per cent elongation, or type of failure.

3. The Hencky-vonMises (constant octahedral shear stress) theory of yielding cannot be extended to include the fracture of mild steel cylinders, especially at stress ratios above 2.0.

4. True octahedral shear stress increases non-linearly with increase in true stress ratio. The curve which has the equation $\sqrt{\bar{\sigma}_a^2 + \bar{\sigma}_t^2} = 105{,}000$ psi closely approximates the results of testing.

5. Stress concentration, coupled with low temperature and biaxial stressing, may lead to cleavage fracture.

6. Cleavage fracture may occur when steel shows normal failure stresses and per cent elongation; it is not by itself prima facie evidence of brittle behavior. Brittle behavior is characterized by low per cent elongation and abnormally small failure stresses in addition to cleavage fracture.

7. Roughness of specimen finish has a first order effect on strength, causing a measurable decrease in $\bar{\tau}_n$ which is more pronounced at higher values of $\bar{n}$.

8. There is no appreciable size effect so far as specimen wall thickness is concerned.

9. Heat treatment apparently does not increase the ultimate strength of mild steel under the conditions of this type of testing.

10. The normal shear fracture is to be expected, in the absence of undue stress concentrations, in mild steel cylinders tested at stress ratios from 1 to 4, at temperatures down to -50° F.

11. Regardless of the failure criterion adopted, it may be expected that run-of-the-mill mild steel will fail at stresses as much as 15% above or below those predicted, as a result of variation in surface finish, chemical composition, and microstructure of the steel.

Recommendations

1. It is felt that there is much work left to be done in the area of this thesis. The literature reveals that very few tests have been conducted with a view to determining the effect of biaxial stress on the failure of mild steel, particularly at higher stress ratios.

2. Were the authors to continue their researches, the following changes would be made in procedure, providing time and material available permitted:

   a. Specimens would be finished by grinding, especially internally.

   b. Low-temperature testing would be discontinued in favor of testing at room temperature.

   c. A high-capacity mechanical pumping system would replace the present manual system.

   d. Testing would proceed at the higher stress ratios ($x > 4$) to amplify and confirm data already gathered, so as to complete the locus of failures for stress ratios greater than 1.

   e. Time permitting, the test setup would be modified to allow testing at stress ratios below 1, in order to obtain further information on the locus of failures and the anisotropy of specimen material.

   f. Personnel permitting, data on yield point would be taken in an attempt to verify current theories of yielding. This would involve the use of a clip type strain gage as explained in reference (4) or some type of mechanical strain gaging or photogrid.

APPENDIX I

PIPE NO. 2 TEST NO. 1 AMBIENT TEMP 66 °F STRESS RATIO 2:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.051	0.053	0.057	0.055
	90°	0.052	0.057	0.057	0.043
	180°	0.056	0.056	0.055	0.049
	270°	0.058	0.055	0.058	
O.D.	0°-180°	2.737	2.740	2.745	2.727*
	90°-270°	2.740	2.741	2.745	

	INITIAL	FINAL
Avg. I.D.	2.630	2.629
Avg. t	0.055	0.049
L	3.812	4.141
Area	0.054	0.412

TEST DATA

TENSION lbs	HYD. PRESS. lbs
1677	1000
3354	2000
5031	3000
6708	4000
8380	5000
10000	6000
11740	7000
13420	8000
15100	9000
16770	10000
18450	11000
20120	12000
21300	13000
23480	14000
25150	15000
BREAK DATA	
22550	15000

TIME	mv	TEMP °F
0	0	66
15	-1.40	
20	-1.80	
25	-1.85	
30	-1.97	
35	-2.04	
45	-2.17	
55	-2.30	
60	-2.30	
BREAK	-2.21	-38.9

TEST RESULTS AT FAILURE

% Reduction in Area	9.2	σ_a	65,600	psi
% Elongation	8.6	σ_t	34,950	psi
Type Failure	~~Ductile~~ SHEAR	σ_r	[illegible]730	psi
Failure Temp. °F	-38.9	$\bar{\sigma}_a$	73,700	psi
n	1.88	$\bar{\sigma}_t$	38,400	psi
N	1.92	$\bar{\sigma}_r$	[illegible]730	psi
		$\bar{\tau}_n$	27,100	psi

REMARKS:

* Diameter obtained from girth of specimen after failure.

PIPE NO. 5 TEST NO. 2 AMBIENT TEMP 58 °F STRESS RATIO 3:1

DIMENSIONS OF TEST SECTION

		INITIAL		FINAL
	LEFT	CENTER	RIGHT	
t 0°	0.074	0.075	0.074	0.057
t 90°	0.076	0.075	0.072	0.053
t 180°	0.075	0.074	0.073	0.054
t 270°	0.072	0.072	0.073	0.056
O.D. 0°-180°	2.773	2.774	2.774	2.654*
O.D. 90°-270°	2.772	2.772	2.772	-

	INITIAL	FINAL
Avg. I.D.	2.625	2.544
Avg. t	0.074	0.055
L	3.703	4.812
Area	0.627	0.[illegible]54

TEST DATA

TENSION lbs	HYD. PRESS. lbs
2790	1000
5580	2000
8370	3000
11160	4000
13950	5000
16750	6000
19540	7000
22340	8000
25120	9000
27900	10000
30700	11000
33500	12000
36250	13000
39060	14000
BREAK DATA	
38000	14500

TIME	mv	TEMP °F
0	0	58
15	-1.82	
30	-2.07	
45	-2.25	
60	-2.38	
70	-2.38	
BREAK	-2.15	-44.8

TEST RESULTS AT FAILURE

% Reduction in Area	27.6	σ_a	72,300	psi
% Elongation	29.5	σ_t	23,000	psi
Type Failure	~~Brittle~~ SHEAR	σ_r	704	psi
Failure Temp. °F	-44.8	$\bar{\sigma}_a$	101,000	psi
n	3.14	$\bar{\sigma}_t$	31,750	psi
N	3.08	$\bar{\sigma}_r$	704	psi
		$\bar{\tau}_n$	42,000	psi

REMARKS:

* Diameter ovtained from girth of specimen after failure.

PIPE NO. 18 TEST NO. 3 AMBIENT TEMP 69.4 °F STRESS RATIO 3:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.104	0.103	0.103	0.075
	90°	0.102	0.105	0.106	0.069
	180°	0.098	0.102	0.102	0.067
	270°	0.104	0.105	0.106	0.077
O.D.	0°-180°	2.814	2.814	2.814	2.526
	90°-270°	2.813	2.814	2.814	2.541

	INITIAL	FINAL
Avg. I.D.	2.608	2.389
Avg. t	0.103	0.072
L	4	5
Area	0.876	0.556

TEST DATA

TENSION lbs	HYD. PRESS. lbs
20100	8000
23600	9000
25000	10000
27600	11000
30200	12000
32680	13000
35160	14000
37540	15000
40000	16000
42500	17000
BREAK DATA	
59400	5000*

TIME	mv	TEMP °F
0	0.07	69.4
10	-1.12	
30	-1.69	
60	-2.09	
80	-2.40	
100	-2.40	
BREAK	-2.08	-29.4

TEST RESULTS AT FAILURE

% Reduction in Area	36.5	σ_a	70,800	psi
% Elongation	25	σ_t	6,150	psi
Type Failure	~~Ductile~~ D Shear	σ_r	243	psi
Failure Temp. °F	-29.4	$\bar{\sigma}_a$	109,000	psi
n	11.5	$\bar{\sigma}_t$	8,060	psi
N	13.5	$\bar{\sigma}_r$	243	psi
		$\bar{\tau}_n$	49,200	psi

REMARKS:

* Lost oil pressure due to lack of oil supply.

PIPE NO. 13 TEST NO. 4 AMBIENT TEMP 69.5 °F STRESS RATIO 4:1

DIMENSIONS OF TEST SECTION

		INITIAL		FINAL
	LEFT	CENTER	RIGHT	
t 0°	0.084	0.085	0.085	0.060
t 90°	0.081	0.083	0.083	0.059
t 180°	0.081	0.084	0.084	0.059
t 270°	0.080	0.081	0.082	0.058
O.D. 0°-180°	2.803	2.803	2.804	2.584
O.D. 90°-270°	2.803	2.803	2.803	2.615

	INITIAL	FINAL
Avg. I.D.	2.637	2.481
Avg. t	0.083	0.059
L	3.50	4.39
Area	0.709	0.471

TEST DATA

TENSION lbs	HYD. PRESS. lbs
19220	5000
23060	6000
26900	7000
30750	8000
34600	9000
38445	10000
42290	11000
46135	12000
49980	13000
BREAK DATA	
45000	12000

TIME	mv	TEMP °F
0	0	69.5
30	-1.29	
40	-1.85	
50	-1.90	
60	-1.65	
BREAK	-1.47	1.1

TEST RESULTS AT FAILURE

% Reduction in Area	33.6	σ_a	76,400	psi
% Elongation	25.4	σ_t	18,500	psi
Type Failure	Shear	σ_r	584	psi
Failure Temp. °F	1.1	$\bar{\sigma}_a$	107,800	psi
n	4.12	$\bar{\sigma}_t$	24,500	psi
K	4.4	$\bar{\sigma}_r$	584	psi
		$\bar{\tau}_n$	46,200	psi

REMARKS:

PIPE NO. 12 TEST NO. 5 AMBIENT TEMP 70 °F STRESS RATIO 1:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.056	0.057	0.060	0.051
	90°	0.057	0.060	0.059	0.043
	180°	0.058	0.060	0.060	0.037
	270°	0.057	0.058	0.058	0.041
O.D.	0°-180°	2.806	2.810	2.810	2.963
	90°-270°	2.805	2.809	2.809	2.909

	INITIAL	FINAL
Avg. I.D.	2.692	2.842
Avg. t	0.058	0.043
L	2.0	2.242
Area	0.501	0.390

TEST DATA

TENSION lbs	HYD. PRESS. lbs
7630	12000
8260	13000
8900	14000
9530	15000
10170	16000
10850	17000
11440	18000
12080	19000
12710	20000
13350	21000
13980	22000
14620	23000
15250	24000
BREAK DATA	
2 6000	23500

TIME	mv	TEMP °F
0	0	70
25	-2.46	
60	-2.53	
65	-2.53	
BREAK	-2.45	-48

TEST RESULTS AT FAILURE

% Reduction in Area	24.2	σ_a	77,900	psi
% Elongation	12.1	σ_t	53,000	psi
Type Failure	Shear	σ_r	1,140	psi
Failure Temp. °F	-48	$\bar{\sigma}_a$	104,100	psi
n	1.47	$\bar{\sigma}_t$	75,300	psi
E	1.38	$\bar{\sigma}_r$	1,140	psi
		$\bar{\tau}_n$	42,300	psi

REMARKS:

Pulled at n = 1 until pressure equaled 23,500 lbs and then increased tension to failure.

PIPE NO. 22 TEST NO. 6 AMBIENT TEMP 69 °F STRESS RATIO 3:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.064	0.067	0.067	0.043
	90°	0.065	0.067	0.067	0.043
	180°	0.064	0.067	0.067	0.043
	270°	0.0640	0.066	0.067	0.041
O.D.	0°-180°	2.813	2.814	2.814	2.735
	90°-270°	2.814	2.814	2.815	2.709

	INITIAL	FINAL
Avg. I.D.	2.682	2.636
Avg. t	0.066	0.043
L	2.0	2.344
Area	0.569	0.362

TEST DATA

TENSION lbs	HYD. PRESS. lbs
11600	4000
14600	5000
17500	6000
20400	7000
23300	8000
26200	9000
29150.	10000
32000	11000
34900	12000
37850	13000
BREAK DATA	
35400	13000

TIME	mv	TEMP °F
0	0	69
20	-2.15	
30	-2.15	
40	-2.13	
Break	-2.02	-26.9

TEST RESULTS AT FAILURE

% Reduction in Area 36.4
% Elongation 17.2
Type Failure Cleavage-Shear
Failure Temp. °F -26.9
n 2.90
N 2.90

σ_a 74,700 psi
σ_t 25,700 psi
σ_r 632 psi
$\bar{\sigma}_a$ 112,500 psi
$\bar{\sigma}_t$ 38,700 psi
$\bar{\sigma}_r$ 632 psi
$\bar{\tau}_n$ 46,600 psi

REMARKS:

PIPE NO. 17 TEST NO. 7 AMBIENT TEMP 70 °F STRESS RATIO 4:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.086	0.088	0.088	0.069
	90°	0.084	0.088	0.088	0.068
	180°	0.086	0.089	0.088	0.067
	270°	0.086	0.089	0.088	0.073
O.D.	0°-180°	2.795	2.795	2.795	2.698
	90°-270°	2.795	2.795	2.795	2.699

	INITIAL	FINAL
Avg. I.D.	2.621	2.561
Avg. t	0.087	0.069*
L	2.0	2.50
Area	0.740	0.569

TEST DATA

TENSION lbs	HYD. PRESS. lbs
19620	5000
23550	6000
27400	7000
31300	8000
35250	9000
39150	10000
43050	11000
BREAK DATA	
43000	11000

TIME	mv	TEMP °F
0	0	70
30	-2.20	
40	-2.22	
50	-2.22	
Break	-2.02	-25.75

TEST RESULTS AT FAILURE

% Reduction in Area	23.1	σ_a	65,990	psi
% Elongation	25	σ_t	16,100	psi
Type Failure	Cleavage-Shear	σ_r	535	psi
Failure Temp. °F	-25.75	$\bar{\sigma}_a$	85,100	psi
n	4.09	$\bar{\sigma}_t$	19,850	psi
$\bar{n}$	4.28	$\bar{\sigma}_r$	535	psi
		$\bar{\tau}_m$	36,200	psi

REMARKS:

Internal wall had a tool notch 0.008" in depth at the apparent commencement of the failure.

PIPE NO. 5 TEST NO. 9 AMBIENT TEMP 70 °F STRESS RATIO 4:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.065	0.065	0.065	0.052
	90°	0.068	0.068	0.067	0.054
	180°	0.065	0.064	0.065	0.058
	270°	0.065	0.065	0.066	0.056
O.D.	0°-180°	2.785	2.787	2.787	2.608
	90°-270°	2.793	2.791	2.790	2.612

	INITIAL	FINAL
Avg. I.D.	2.657	2.500
Avg. t	0.066	0.055
L	2.0	2.605
Area	0.564	0.441

TEST DATA

TENSION lbs	HYD. PRESS. lbs
15890	4000
19880	5000
23870	6000
27760	7000
31690	8000
35630	9000
BREAK DATA	
33800	9000

TIME	mv	TEMP °F
0	0	70
45	-2.25	
60	-2.35	
70	-2.35	
Break	-2.21	-35.4

TEST RESULTS AT FAILURE

% Reduction in Area	21.8	σ_a	72,100	psi
% Elongation	30.3	σ_t	17,580	psi
Type Failure	Shear	σ_r	438	psi
Failure Temp. °F	-35.4	$\bar{\sigma}_a$	86,100	psi
n	4.10	$\bar{\sigma}_t$	19,870	psi
N	4.34	$\bar{\sigma}_r$	438	psi
		$\bar{\tau}_n$	36,700	psi

REMARKS:

PIPE NO. 20 TEST NO. 10 AMBIENT TEMP 67 °F STRESS RATIO 4:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.094	0.094	0.095	0.066
	90°	0.094	0.094	0.095	0.067
	180°	0.096	0.094	0.095	0.067
	270°	0.094	0.095	0.096	0.068
O.D.	0°-180°	2.800	2.800	2.800	2.570
	90°-270°	2.800	2.800	2.800	2.614

	INITIAL	FINAL
Avg. I.D.	2.610	2.456
Avg. t	0.095	0.068
L	2.0	2.484
Area	0.808	0.535

TEST DATA

TENSION lbs	HYD. PRESS. lbs
19525	5000
23390	6000
27790	7000
31125	8000
35090	9000
39050	10000
42910	11000
46780	12000
50650	13000
BREAK DATA	
49800	13000

TIME	mv	TEMP °F
0	+0.05	67
30	-1.85	
60	-2.07	
70	-2.10	
80	-2.10	
Break	-2.06	-34.2

TEST RESULTS AT FAILURE

% Reduction in Area	33.8	σ_a	70,100	psi
% Elongation	24.2	σ_t	17,370	psi
Type Failure	Shear	σ_r	631	psi
Failure Temp. °F	-34.2	$\bar{\sigma}_a$	103,800	psi
n	4.04	$\bar{\sigma}_t$	22,800	psi
K	4.55	$\bar{\sigma}_r$	631	psi
		$\bar{\tau}_n$	44,300	psi

REMARKS:

PIPE NO. 16 TEST NO. 11 AMBIENT TEMP 68 °F STRESS RATIO 2:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.074	0.075	0.073	0.060
	90°	0.072	0.073	0.073	0.063
	180°	0.073	0.074	0.074	0.064
	270°	0.074	0.076	0.074	0.063
O.D.	0°-180°	2.799	2.802	2.805	2.765
	90°-270°	2.799	2.802	2.805	2.785

	INITIAL	FINAL
Avg. I.D.	2.654	2.641
Avg. t	0.074	0.062
L	2.0	2.330
Area	0.634	0.526

TEST DATA

TENSION lbs	HYD. PRESS. lbs
15690	9000
17470	10000
19520	11000
21030	12000
22810	13000
24590	14000
26370	15000
28150	16000
29930	17000
31710	18000
33490	19000
35250	20000
37030	21000
BREAK DATA	
37800	21000

TIME	mv	TEMP °F
0	-0.15	68
30	-2.30	
40	-2.32	
50	-2.34	
Break	-2.15	-28

TEST RESULTS AT FAILURE

% Reduction in Area	17	σ_a	77,300	psi
% Elongation	16.5	σ_t	36,600	psi
Type Failure	Shear	σ_r	1,020	psi
Failure Temp. °F	-28	$\bar{\sigma}_a$	93,000	psi
n	2.11	$\bar{\sigma}_t$	43,400	psi
m	2.14	$\bar{\sigma}_r$	1,020	psi
		$\bar{\tau}_n$	36,850	psi

REMARKS:

PIPE NO. 21 TEST NO. 12 AMBIENT TEMP 70 °F STRESS RATIO 4:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.086	0.089	0.090	0.066
	90°	0.087	0.090	0.090	0.068
	180°	0.087	0.090	0.088	0.070
	270°	0.088	0.089	0.088	0.068
O.D.	0°-180°	2.792	2.793	2.793	2.609
	90°-270°	2.793	2.793	2.793	2.651

	INITIAL	FINAL
Ave. I.D.	2.615	2.494
Ave. t	0.088	0.068
L	2.0	2.312
Area	0.744	0.548

TEST DATA

TENSION lbs	HYD. PRESS. lbs
19500	5000
23300	6000
27120	7000
30940	8000
34760	9000
38600	10000
42400	11000
46200	12000
BREAK DATA	
47200	12000

TIME	mv	TEMP °F
0	+0.05	70
50	-2.04	
60	-2.25	
90	-2.49	
120	-2.59	
160	-2.60	
Break	-2.50	-50.6

TEST RESULTS AT FAILURE

% Reduction in Area	26.4	σ_a	71,250	psi
% Elongation	15.6	σ_t	17,250	psi
Type Failure	Shear	σ_r	583	psi
Failure Temp. °F	-50.6	$\bar{\sigma}_a$	97,900	psi
n	4.13	$\bar{\sigma}_t$	21,400	psi
K	4.56	$\bar{\sigma}_r$	583	psi
		$\bar{\tau}_n$	40,800	psi

REMARKS:

PIPE NO. 10 TEST NO. 13 AMBIENT TEMP 72 °F STRESS RATIO 3:1

DIMENSIONS OF TEST SECTION

		INITIAL			FINAL
		LEFT	CENTER	RIGHT	
t	0°	0.085	0.079	0.075	0.064
	90°	0.083	0.079	0.075	0.058
	180°	0.083	0.078	0.076	0.059
	270°	0.083	0.079	0.075	0.060
O.D.	0°-180°	2.814	2.814	2.814	2.750
	90°-270°	2.815	2.814	2.814	2.721

	INITIAL	FINAL
Avg. I.D.	2.656	2.616
Avg. t	0.079	0.060
L	2.0	2.312
Area	0.677	0.504

TEST DATA

TENSION lbs	HYD. PRESS. lbs
14340	5000
17180	6000
20050	7000
22920	8000
25790	9000
28660	10000
31530	11000
34400	12000
37270	13000
40140	14000
BREAK DATA	
37400	14000

TIME	mv	TEMP °F
0	0	72
25	-1.50	
35	-1.65	
45	-1.70	
55	-1.74	
60	-1.74	
Break	-1.60	-3.0

TEST RESULTS AT FAILURE

% Reduction in Area	25.5
% Elongation	15.6
Type Failure	Shear
Failure Temp. °F	-3.0
n	2.83
$\bar{n}$	2.94

σ_a	64,800	psi
σ_t	22870	psi
σ_r	680	psi
$\bar{\sigma}_a$	87,200	psi
$\bar{\sigma}_t$	29,650	psi
$\bar{\sigma}_r$	680	psi
$\bar{\tau}_n$	36,000	psi

REMARKS:

PIPE NO. 19 TEST NO. 14 AMBIENT TEMP 75 °F STRESS RATIO 2:1

DIMENSIONS OF TEST SECTION

		INITIAL		FINAL
	LEFT	CENTER	RIGHT	
t 0°	0.078	0.076	0.076	0.064
t 90°	0.077	0.077	0.077	0.064
t 180°	0.077	0.077	0.077	0.061
t 270°	0.077	0.076	0.077	0.061
O.D. 0°-180°	2.798	2.799	2.798	2.802
O.D. 90°-270°	2.798	2.799	2.799	2.783

	INITIAL	FINAL
Avg. I.D.	2.645	2.668
Avg. t	0.077	0.062
L	2.0	2.516
Area	0.657	0.531

TEST DATA

TENSION lbs	HYD. PRESS. lbs
16320	10000
17855	11000
19590	12000
21225	13000
22860	14000
24495	15000
26130	16000
27765	17000
28400	18000
30035	19000
31670	20000
33305	21000
35900	22000
BREAK DATA	
37500	23000

TIME	mv	TEMP °F
0	0	75
55	-2.15	
65	-2.25	
75	-2.33	
90	-2.38	
100	-2.43	
110	-2.43	
Break	-2.18	-28.2

TEST RESULTS AT FAILURE

% Reduction in Area	19.2	σ_a	76,200	psi
% Elongation	25.8	σ_t	36,400	psi
Type Failure	Shear	σ_r	1,120	psi
Failure Temp. °F	-28.2	$\bar{\sigma}_a$	92,600	psi
n	2.09	$\bar{\sigma}_t$	48,100	psi
$\bar{n}$	1.92	$\bar{\sigma}_r$	1,120	psi
		$\bar{\tau}_E$	38,500	psi

REMARKS:

PIPE NO. 9 TEST NO. 15 AMBIENT TEMP 74 °F STRESS RATIO 2:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.069	0.071	0.073	0.058
	90°	0.067	0.070	0.071	0.058
	180°	0.067	0.069	0.071	0.057
	270°	0.066	0.069	0.072	0.056
O.D.	0°-180°	2.806	2.807	2.808	2.792
	90°-270°	2.807	2.806	2.808	2.782

	INITIAL	FINAL
Avg. I.D.	2.667	2.672
Avg. t	0.070	0.057
L	2.0	2.359
Area	0.601	0.488

TEST DATA

TENSION lbs	HYD. PRESS. lbs
15490	9000
17205	10000
18920	11000
20635	12000
22350	13000
24065	14000
25780	15000
27495	16000
29220	17000
30935	18000
BREAK DATA	
31250	18000

TIME	mv	TEMP °F
0	0	74
15	-1.64	
25	-1.79	
35	-1.86	
45	-1.95	
55	-1.99	
65	-2.01	
70	-2.01	
Break	-1.96	-18.3

TEST RESULTS AT FAILURE

% Reduction in Area	18.6	σ_a	68,200	psi
% Elongation	17.9	σ_t	33,350	psi
Type Failure	Shear	σ_r	875	psi
Failure Temp. °F	-18.3	$\bar{\sigma}_a$	84,700	psi
n	2.04	$\bar{\sigma}_t$	41,000	psi
N	2.05	$\bar{\sigma}_r$	875	psi
		$\bar{\tau}_m$	34,000	psi

REMARKS:

PIPE NO. 1 TEST NO. 16 AMBIENT TEMP 74 °F STRESS RATIO 2:1

DIMENSIONS OF TEST SECTION

		INITIAL			FINAL
		LEFT	CENTER	RIGHT	
t	0°	0.075	0.074	0.073	0.062
	90°	0.077	0.075	0.076	0.061
	180°	0.074	0.073	0.074	0.061
	270°	0.073	0.073	0.072	0.062
O.D.	0°-180°	2.793	2.794	2.795	2.751
	90°-270°	2.793	2.793	2.794	2.761

	INITIAL	FINAL
Avg. I.D.	2.646	2.633
Avg. t	0.074	0.062
L	2.0	2.203
Area	0.631	0.520

TEST DATA

TENSION lbs	HYD. PRESS. lbs
16200	9000
18005	10000
19810	11000
21615	12000
23420	13000
25225	14000
27030	15000
28835	16000
30640	17000
32445	18000
34250	19000
36055	20000
BREAK DATA	
37000	20000

TIME	mv	TEMP °F
0	0	74
35	-2.05	
45	-2.31	
55	-2.40	
65	-2.45	
75	-2.45	
Break	-2.40	-40.7

TEST RESULTS AT FAILURE

% Reduction in Area	17.6	σ_a	75,500	psi
% Elongation	10.1	σ_t	34,800	psi
Type Failure	Shear	σ_r	973	psi
Failure Temp. °F	-40.7	$\bar{\sigma}_a$	90,600	psi
n	2.16	$\bar{\sigma}_t$	41,600	psi
$\bar{n}$	2.17	$\bar{\sigma}_r$	973	psi
		$\bar{\tau}_n$	36,800	psi

REMARKS:

PIPE NO. 15 TEST NO. 17 AMBIENT TEMP 70 °F STRESS RATIO 4:1

DIMENSIONS OF TEST SECTION

		INITIAL			FINAL
		LEFT	CENTER	RIGHT	
t	0°	0.077	0.078	0.076	0.059
	90°	0.077	0.077	0.074	0.060
	180°	0.076	0.077	0.074	0.060
	270°	0.077	0.077	0.075	0.057
O.D.	0°-180°	2.811	2.811	2.810	2.667
	90°-270°	2.811	2.811	2.810	2.678

	INITIAL	FINAL
Avg. I.D.	2.659	2.554
Avg. t	0.076	0.059
L	2.0	2.718
Area	0.652	0.484

TEST DATA

TENSION lbs	HYD. PRESS. lbs
16970	4000
19980	5000
23930	6000
28030	7000
31970	8000
36020	9000
39870	10000
BREAK DATA	
40000	10000

TIME	mv	TEMP °F
0	0	70
30	-1.49	
45	-1.60	
55	-1.70	
70	-1.80	
80	-1.78	
90	-1.78	
Break	-1.67	-8.3

TEST RESULTS AT FAILURE

% Reduction in Area	25.8	σ_a	69,500	psi
% Elongation	35.9	σ_t	17,030	psi
Type Failure	Shear	σ_r	486	psi
Failure Temp. °F	-8.3	$\bar{\sigma}_a$	93,000	psi
n	4.08	$\bar{\sigma}_t$	21,000	psi
m	4.42	$\bar{\sigma}_r$	486	psi
		$\bar{\tau}_m$	39,500	psi

REMARKS:

PIPE NO. 11 TEST NO. 18 AMBIENT TEMP 72 °F STRESS RATIO 3:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.077	0.078	0.079	0.061
	90°	0.077	0.077	0.078	0.059
	180°	0.077	0.078	0.079	0.059
	270°	0.078	0.078	0.080	0.059
O.D.	0°-180°	2.808	2.809	2.809	2.724
	90°-270°	2.809	2.809	2.808	2.721

	INITIAL	FINAL
Ave. I.D.	2.653	2.604
Ave. t	0.078	0.059
L	2.0	2.406
Area	0.669	0.494

TEST DATA

TENSION lbs	HYD. PRESS. lbs
11410	4000
14270	5000
17140	6000
19180	7000
22880	8000
25730	9000
28580	10000
31440	11000
34180	12000
37120	13000
39880	14000
BREAK DATA	
40250	14000

TIME	mv	TEMP °F
0	0	72
40	-2.10	
50	-2.19	
60	-2.22	
70	-2.25	
80	-2.25	
Break	-2.02	-23.3

TEST RESULTS AT FAILURE

% Reduction in Area	26.2	σ_a	71,400	psi
% Elongation	20.3	σ_t	23,150	psi
Type Failure	Shear	σ_r	680	psi
Failure Temp. °F	-23.3	$\bar{\sigma}_a$	96,100	psi
n	3.08	$\bar{\sigma}_t$	30,000	psi
$\bar{n}$	3.2	$\bar{\sigma}_r$	680	psi
		$\bar{\tau}_n$	39,900	psi

REMARKS:

PIPE NO. 6 TEST NO. 19 AMBIENT TEMP 70 °F STRESS RATIO 4:1

DIMENSIONS OF TEST SECTION

		INITIAL		FINAL
	LEFT	CENTER	RIGHT	
t 0°	0.084	0.083	0.083	0.059
t 90°	0.084	0.083	0.083	0.060
t 180°	0.083	0.083	0.083	0.059
t 270°	0.084	0.083	0.083	0.060
O.D. 0°-180°	2.817	2.816	2.815	2.635
O.D. 90°-270°	2.815	2.816	2.817	2.617

	INITIAL	FINAL
Avg. I.D.	2.650	2.508
Avg. t	0.083	0.059
L	2.0	2.720
Area	0.711	0.475

TEST DATA

TENSION lbs	HYD. PRESS lbs
15890	4000
19880	5000
23870	6000
27860	7000
31850	8000
35840	9000
39830	10000
43820	11000
47810	12000
BREAK DATA	
47350	12000

TIME	mv	TEMP °F
0	0	70
65	-2.18	
85	-2.43	
95	-2.52	
105	-2.53	
115	-2.54	
125	-2.54	
Break	-2.36	-43.1

TEST RESULTS AT FAILURE

% Reduction in Area	33.2	σ_a	77,000	psi
% Elongation	36.0	σ_t	18,620	psi
Type Failure	Shear	σ_r	584	psi
Failure Temp. °F	-43.1	$\bar{\sigma}_a$	113,500	psi
n	4.13	$\bar{\sigma}_t$	24,850	psi
$\bar{n}$	4.56	$\bar{\sigma}_r$	584	psi
		$\bar{\tau}_n$	48,900	psi

REMARKS:

PIPE NO. 23 TEST NO. 20 AMBIENT TEMP 66 °F STRESS RATIO 2:1

DIMENSIONS OF TEST SECTION

		INITIAL		FINAL
	LEFT	CENTER	RIGHT	
t 0°	0.065	0.067	0.069	0.050
t 90°	0.064	0.068	0.069	0.051
t 180°	0.064	0.068	0.069	0.050
t 270°	0.063	0.067	0.068	0.051
O.D. 0°-180°	2.804	2.803	2.803	2.803
O.D. 90°-270°	2.801	2.802	2.804	2.781

	INITIAL	FINAL
Avg. I.D.	2.669	2.691
Avg. t	0.067	0.050
L	2.0	2.296
Area	0.575	0.435

TEST DATA

TENSION lbs	HYD. PRESS. lbs
13300	8000
15080	9000
16860	10000
18640	11000
20420	12000
22200	13000
23920	14000
25760	15000
27540	16000
29320	17000
31100	18000
BREAK DATA	
31300	18000

TIME	mv	TEMP °F
0	+0.06	66
35	-1.40	
45	-1.51	
55	-1.61	
65	-1.71	
75	-1.76	
85	-1.76	
Break	-1.42	-1.0

TEST RESULTS AT FAILURE

% Reduction in Area	24.4
% Elongation	14.8
Type Failure	Shear
Failure Temp. °F	-1.0
n	2.04
m	2.07

σ_a	71,300	psi
σ_t	34,850	psi
σ_r	875	psi
$\bar{\sigma}_a$	94,900	psi
$\bar{\sigma}_t$	45,700	psi
$\bar{\sigma}_r$	875	psi
$\bar{\tau}_n$	38,400	psi

REMARKS:

PIPE NO. 7 TEST NO. 21 AMBIENT TEMP 65 °F STRESS RATIO 3:1

DIMENSIONS OF TEST SECTION

		INITIAL		FINAL
	LEFT	CENTER	RIGHT	
t 0°	0.074	0.075	0.075	0.058
t 90°	0.074	0.074	0.075	0.062
t 180°	0.077	0.076	0.075	0.061
t 270°	0.079	0.080	0.079	0.061
O.D. 0°-180°	2.791	2.792	2.792	2.713
O.D. 90°-270°	2.790	2.791	2.790	2.695

	INITIAL	FINAL
Avg. I.D.	2.639	2.584
Avg. t	0.076	0.060
L	2.0	2.406
Area	0.624	0.499

TEST DATA

TENSION lbs	HYD. PRESS. lbs
15780	6000
18420	7000
21060	8000
23700	9000
26340	10000
28980	11000
31620	12000
34260	13000
36900	14000
39500	15000
BREAK DATA	
41000	15000

TIME	mv	TEMP °F
0	+0.03	65
35	-1.94	
45	-2.04	
55	-2.12	
65	-2.16	
75	-2.17	
Break	-2.05	-34.5

TEST RESULTS AT FAILURE

% Reduction in Area	20.0	σ_a	75,600	psi
% Elongation	20.3	σ_t	25,300	psi
Type Failure	Shear	σ_r	740	psi
Failure Temp. °F	-34.5	$\bar{\sigma}_a$	97,500	psi
n	2.99	$\bar{\sigma}_t$	31,400	psi
$\bar{n}$	3.10	$\bar{\sigma}_r$	740	psi
		$\bar{\sigma}_n$	40,500	psi

REMARKS:

PIPE NO. 24   TEST NO. 22   AMBIENT TEMP 67 °F   STRESS RATIO 2:1

DIMENSIONS OF TEST SECTION

		INITIAL			FINAL
		LEFT	CENTER	RIGHT	
t	0°	0.064	0.064	0.063	0.052
	90°	0.066	0.065	0.065	0.047
	180°	0.061	0.061	0.060	0.048
	270°	0.062	0.061	0.059	0.053
O.D.	0°-180°	2.750	2.750	2.749	2.750
	90°-270°	2.753	2.751	2.749	2.754

	INITIAL	FINAL
Avg. I.D.	2.626	2.652
Avg. t	0.062	0.050
L	2.0	2.296
Area	0.524	0.423

TEST DATA

TENSION lbs	HYD. PRESS. lbs
11730	7000
13285	8000
14860	9000
16395	10000
17950	11000
19505	12000
21060	13000
22615	14000
24170	15000
25725	16000
27280	17000
28860	18000
BREAK DATA	
33000	20000

TIME	mv	TEMP °F
0	+0.03	67
55	-2.20	
75	-2.37	
85	-2.53	
95	-2.60	
115	-2.60	
Break	-2.29	-42.3

TEST RESULTS AT FAILURE

% Reduction in Area	19.3	σ_a	83,000	psi
% Elongation	14.8	σ_t	41,300	psi
Type Failure	Shear-Cleavage	σ_r	970	psi
Failure Temp. °F	-42.3	$\bar{\sigma}_a$	103,000	psi
n	2.01	$\bar{\sigma}_t$	51,600	psi
$\bar{n}$	2.0	$\bar{\sigma}_r$	970	psi
		$\bar{\tau}_n$	41,900	psi

REMARKS:

Specimen not annealed

PIPE NO. 26 TEST NO. 23 AMBIENT TEMP 68 °F STRESS RATIO 1:1

DIMENSIONS OF TEST SECTION

		INITIAL			FINAL
		LEFT	CENTER	RIGHT	
t	0°	0.054	0.055	0.054	0.046
	90°	0.053	0.054	0.053	0.046
	180°	0.053	0.054	0.053	0.047
	270°	0.053	0.053	0.053	0.047
O.D.	0°-180°	2.766	2.765	2.766	3.120*
	90°-270°	2.768	2.767	2.767	-

	INITIAL	FINAL
Avg. I.D.	2.660	3.027
Avg. t	0.053	0.046
L	2.0	2.250
Area	0.451	0.449

TEST DATA

TENSION lbs	HYD. PRESS. lbs
6940	12000
75000	13000
8090	14000
8620	15000
9230	16000
9770	17000
10350	18000
10900	19000
11500	20000
12050	21000
12600	22000
13250	23000
13800	24000
BREAK DATA	
14500	23500

TIME	mv	TEMP °F
0	0	68
20	-1.35	
40	-1.64	
60	-1.60	
Break	-1.50	-2.2

TEST RESULTS AT FAILURE

% Reduction in Area	0.5	σ_a	60,400	psi
% Elongation	12.5	σ_t	57,350	psi
Type Failure	Shear	σ_r	1,140	psi
Failure Temp. °F	-2.2	$\bar{\sigma}_a$	69,100	psi
n	1.05	$\bar{\sigma}_t$	74,500	psi
$\bar{n}$	0.93	$\bar{\sigma}_r$	1,140	psi
		τ_n	32,800	psi

REMARKS:

* Diameter obtained from girth of specimen after failure.

PIPE NO. 25 TEST NO. 24 AMBIENT TEMP 70 °F STRESS RATIO 1:1

DIMENSIONS OF TEST SECTION

		INITIAL			FINAL
		LEFT	CENTER	RIGHT	
t	0°	0.048	0.049	0.048	-
	90°	0.046	0.048	0.046	-
	180°	0.047	0.047	0.046	-
	270°	0.046	0.046	0.045	-
O.D.	0°-180°	2.749	2.749	2.749	-
	90°-270°	2.749	2.749	2.749	-

	INITIAL	FINAL
Avg. I.D.	2.655	-
Avg. t	0.047	-
L	2.0	-
Area	0.392	-

TEST DATA

TENSION lbs	HYD. PRESS. lbs
6870	12000
7470	13000
8000	14000
8580	15000
9150	16000
9750	17000
10300	18000
10850	19000
11440	20000
11980	21000
12560	22000
BREAK DATA	
12500	21000

TIME	mv	TEMP °F
0	0	70
30	-1.68	
50	-2.05	
75	-2.18	
90	-2.15	
Break	-1.90	-20

TEST RESULTS AT FAILURE

% Reduction in Area	-	σ_a	60,800	psi
% Elongation	-	σ_t	57,600	psi
Type Failure	Shear	σ_r	1,020	psi
Failure Temp. °F	-20	$\bar{\sigma}_a$	-	psi
n	1.05	$\bar{\sigma}_t$	-	psi
$\bar{n}$	-	$\bar{\sigma}_r$	-	psi
		$\bar{\tau}_n$	-	psi

REMARKS:

Specimen broke in tension alone after initial fracture since load was not removed after initial fracture. Final dimensions are therefore not accurate and are not given.

PLATE 23

PIPE NO. 28 TEST NO. 25 AMBIENT TEMP 68 °F STRESS RATIO 2:1

DIMENSIONS OF TEST SECTION

		INITIAL			FINAL
		LEFT	CENTER	RIGHT	
t	0°	0.052	0.052	0.051	0.045
	90°	0.052	0.051	0.051	0.045
	180°	0.054	0.054	0.051	0.048
	270°	0.054	0.054	0.053	0.048
O.D.	0°-180°	2.754	2.754	2.754	2.754
	90°-270°	2.750	2.751	2.751	2.754

	INITIAL	FINAL
Avg. I.D.	2.649	2.661
Avg. t	0.052	0.0465
L	2.0	2.218
Area	0.441	0.396

TEST DATA

TENSION lbs	HYD. PRESS. lbs
10070	6000
11740	7000
13410	8000
15080	9000
16750	10000
18420	11000
20090	12000
21760	13000
23430	14000
BREAK DATA	
22500	13500

TIME	mv	TEMP °F
0	-0.03	68
55	-1.61	
65	-2.10	
75	-2.23	
85	-2.30	
100	-2.44	
110	-2.44	
Break	-2.20	-37.0

TEST RESULTS AT FAILURE

% Reduction in Area	10.4	σ_a	67,400	psi
% Elongation	10.9	σ_t	33,400	psi
Type Failure	Shear	σ_r	660	psi
Failure Temp. °F	-37.0	$\bar{\sigma}_a$	75,200	psi
n	2.02	$\bar{\sigma}_t$	37,600	psi
r	2.0	$\bar{\sigma}_r$	660	psi
		τ_n	29,600	psi

REMARKS:

PIPE NO. 27 TEST NO. 26 AMBIENT TEMP 70 °F STRESS RATIO 3:1

DIMENSIONS OF TEST SECTION

		INITIAL		FINAL
	LEFT	CENTER	RIGHT	
t 0°	0.050	0.050	0.051	0.040
t 90°	0.050	0.051	0.050	0.043
t 180°	0.050	0.050	0.051	0.046
t 270°	0.050	0.050	0.050	0.044
O.D. 0°-180°	2.752	2.753	2.754	2.670
O.D. 90°-270°	2.752	2.753	2.755	2.650

	INITIAL	FINAL
Avg. I.D.	2.653	2.574
Ave. t	0.050	0.043
L	2.0	2.406
Area	0.425	0.353

TEST DATA

TENSION lbs	HYD. PRESS. lbs
8545	3000
11375	4000
14205	5000
17035	6000
19865	7000
22695	8000
BREAK DATA	
22250	8000

TIME	mv	TEMP °F
0	-0.05	70
15	-1.75	
25	-1.80	
35	-1.95	
45	-1.97	
Break	-1.90	-17.2

TEST RESULTS AT FAILURE

% Reduction in Area	16.95	σ_a	62,400	psi
% Elongation	20.3	σ_t	20,600	psi
Type Failure	Shear	σ_r	390	psi
Failure Temp. °F	-17.2	$\bar{\sigma}_a$	74,400	psi
n	3.02	$\bar{\sigma}_t$	23,250	psi
$\bar{n}$	3.2	$\bar{\sigma}_r$	390	psi
		$\bar{\tau}_n$	30,900	psi

REMARKS:

Specimen bulged near left end while inserting plugs but the failure appeared to be normal.

PIPE NO. 29 TEST NO. 27 AMBIENT TEMP 67 °F STRESS RATIO 1:1

DIMENSIONS OF TEST SECTION

		INITIAL		FINAL
	LEFT	CENTER	RIGHT	
t 0°	0.053	0.053	0.051	0.041
t 90°	0.053	0.052	0.051	0.038
t 180°	0.053	0.052	0.051	0.037
t 270°	0.053	0.053	0.052	0.036
O.D. 0°-180°	2.772	2.772	2.771	3.430*
O.D. 90°-270°	2.771	2.772	2.771	.-

	INITIAL	FINAL
Avg. I.D.	2.568	3.354
Avg. t	0.052	0.038
L	2.0	2.375
Area	0.443	0.404

TEST DATA

TENSION lbs	HYD. PRESS. lbs
6950	12000
7530	13000
8100	14000
8710	15000
9260	16000
9900	17000
10450	18000
11030	19000
11630	20000
12150	21000
12800	22000
BREAK DATA	
13800	22000

TIME	mv	TEMP °F
0	-0.01	67
30	-1.75	
40	-1.95	
55	-1.97	
65	-1.97	
Break	-1.62	-8.5

TEST RESULTS AT FAILURE

% Reduction in Area	8.8	σ_a	58,100	psi
% Elongation	18.7	σ_t	55,000	psi
Type Failure	Shear	σ_r	1,070	psi
Failure Temp. °F	-8.5	$\bar{\sigma}_a$	81,000	psi
n	1.06	$\bar{\sigma}_t$	94,400	psi
m	0.86	$\bar{\sigma}_r$	1,070	psi
		$\bar{\tau}_m$	31,550	psi

REMARKS:

Diameter obtained from girth of specimen after failure.

PIPE NO. 30 TEST NO. 28 AMBIENT TEMP 69 °F STRESS RATIO 1:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.055	0.056	0.055	0.051
	90°	0.054	0.055	0.054	0.051
	180°	0.055	0.055	0.055	0.051
	270°	0.055	0.056	0.055	0.051
O.D.	0°-180°	2.736	2.736	2.737	2.955*
	90°-270°	2.736	2.737	2.737	-

	INITIAL	FINAL
Avg. I.D.	2.626	2.853
Avg. t	0.055	0.051
L	2.0	2.125
Area	0.463	0.465

TEST DATA

TENSION lbs	HYD. PRESS. lbs
6730	12000
7320	13000
7870	14000
8430	15000
9050	16000
9550	17000
10050	18000
10650	19000
11250	20000
11850	21000
12400	22000
12950	23000
13500	24000
14050	25000
14600	26000
15150	27000
BREAK DATA	
15750	27000

TIME	mv	TEMP °F
0	0	69
20	-0.42	
35	-1.86	
65	-2.25	
85	-2.22	
Break	-1.95	-23.3

TEST RESULTS AT FAILURE

% Reduction in Area	0.0	σ_a	64,600	psi
% Elongation	6.2	σ_t	62,700	psi
Type Failure	Shear	σ_r	1,310	psi
Failure Temp. °F	-23.3	$\bar{\sigma}_a$	69,700	psi
n	1.03	$\bar{\sigma}_t$	74,000	psi
$\bar{n}$	0.94	$\bar{\sigma}_r$	1,310	psi
		$\bar{\tau}_n$	33,300	psi

REMARKS:

Diameter obtained from girth of specimen after failure.

PIPE NO. 31 TEST NO. 29 AMBIENT TEMP 67 °F STRESS RATIO 2:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.046	0.051	0.052	0.039
	90°	0.048	0.050	0.053	0.042
	180°	0.049	0.051	0.053	0.039
	270°	0.050	0.051	0.053	0.039
O.D.	0°-180°	2.788	2.788	2.788	2.784
	90°-270°	2.790	2.790	2.790	2.778

	INITIAL	FINAL
Avg. I.D.	2.687	2.701
Avg. t	0.051	0.040
L	2.0	2.156
Area	0.439	0.344

TEST DATA

TENSION lbs	HYD. PRESS. lbs
10490	6000
12250	7000
13950	8000
15375	9000
17510	10000
19250	11000
20950	12000
22720	13000
BREAK DATA	
21,650	13000

TIME	mv	TEMP °F
0	-0.03	67
50	-2.19	
65	-2.46	
85	-2.63	
95	-2.65	
105	-2.68	
Break	-2.45	-50.0

TEST RESULTS AT FAILURE

% Reduction in Area	21.6	σ_a	65,900	psi
% Elongation	7.8	σ_t	33,300	psi
Type Failure	Shear	σ_r	630	psi
Failure Temp. °F	-50.0	$\bar{\sigma}_a$	83,800	psi
n	1.98	$\bar{\sigma}_t$	42700	psi
m	1.96	$\bar{\sigma}_r$	630	psi
		τ_n	34,000	psi

REMARKS:

PIPE NO. 32 TEST NO. 30 AMBIENT TEMP 70 °F STRESS RATIO 3:1

DIMENSIONS OF TEST SECTION

		INITIAL		FINAL
	LEFT	CENTER	RIGHT	
t 0°	0.065	0.064	0.066	0.057
t 90°	0.065	0.064	0.066	0.053
t 180°	0.064	0.064	0.064	0.055
t 270°	0.0640	0.064	0.064	0.051
O.D. 0°-180°	2.792	2.790	2.789	2.682
O.D. 90°-270°	2.793	2.793	2.793	2.725

	INITIAL	FINAL
Avg. I.D.	2.664	2.595
Avg. t	0.064	0.054
L	2.0	2.297
Area	0.549	0.449

TEST DATA

TENSION lbs	HYD. PRESS. lbs
14360	5000
17235	6000
20110	7000
22985	8000
25860	9000
28535	10000
31410	11000
34300	12000
BREAK DATA	
32250	11500

TIME	mv	TEMP °F
0	0	70
35	-1.50	
45	-1.70	
60	-1.75	
70	-1.78	
80	-1.78	
Break	-1.50	0.0

TEST RESULTS AT FAILURE

% Reduction in Area	18.2	σ_a	70,000	psi
% Elongation	14.8	σ_t	23,270	psi
Type Failure	Shear	σ_r	560	psi
Failure Temp. °F	0.0	$\bar{\sigma}_a$	84,800	psi
n	3.00	$\bar{\sigma}_t$	26,850	psi
$\bar{n}$	3.15	$\bar{\sigma}_r$	560	psi
		$\bar{\tau}_n$	35,400	psi

REMARKS:

PIPE NO. 33 TEST NO. 31 AMBIENT TEMP 73 °F STRESS RATIO 1:1

DIMENSIONS OF TEST SECTION

	INITIAL			FINAL
	LEFT	CENTRE	RIGHT	
0°	0.056	0.056	0.056	0.047
90°	0.059	0.058	0.057	0.042
180°	0.056	0.056	0.055	0.044
270°	0.054	0.054	0.055	0.049
O.D. 0°-180°	2.798	2.798	2.798	3.270*
O.D. 90°-270°	2.796	2.795	2.795	-

	INITIAL	FINAL
Ave. I.D.	2.685	3.178
Ave. t	0.056	0.046
L	2.0	2.343
Area	0.482	0.442

TEST DATA

TENSION lbs	HYD. PRESS. lbs
7580	13000
8160	14000
8740	15000
9320	16000
9900	17000
10480	18000
11060	19000
11640	20000
12220	21000
12700	22000
13250	23000
13860	24000
14400	25000
15100	26000
BREAK DATA	
17000	27,500

TIME	mv	TEMP °F
0	-0.06	73
50	-2.25	
60	-2.46	
70	-2.51	
80	-2.51	
Break	-2.30	-36.7

TEST RESULTS AT FAILURE

% Reduction in Area	7.7	σ_a	66,500	psi
% Elongation	17.1	σ_t	64,100	psi
Type Failure	Shear	σ_r	1,338	psi
Failure Temp. °F	-36.7	$\bar{\sigma}_a$	82,000	psi
n	1.04	$\bar{\sigma}_t$	92,400	psi
m	0.887	$\bar{\sigma}_r$	1,338	psi
		$\bar{\tau}_a$	40,900	psi

REMARKS:

* Diameter obtained from girth of specimen after failure.

Specimen was not annealed.

PIPE NO. 34 TEST NO. 32 AMBIENT TEMP 73 °F STRESS RATIO 1 : 2

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.059	0.058	0.055	0.054
	90°	0.059	0.057	0.056	0.054
	180°	0.059	0.058	0.056	0.055
	270°	0.060	0.057	0.056	0.056
O.D.	0°-180°	2.742	2.742	2.741	2.905*
	90°-270°	2.743	2.742	2.741	-

	INITIAL	FINAL
Avg. I.D.	2.626	2.725
Avg. t	0.058	0.055
L	2.0	2.109
Area	0.488	0.490

TEST DATA

TENSION lbs	HYD. PRESS. lbs
7695	14000
8242	15000
8789	16000
9336	17000
9883	18000
10430	19000
10977	20000
11524	21000
12071	22000
12618	23000
13165	24000
13712	25000
14280	26000
BREAK DATA	
15000	27000

TIME	mv	TEMP °F
0	0	73
40	-1.70	
80	-1.80	
95	-2.00	
Break	-1.90	-16.3

TEST RESULTS AT FAILURE

% Reduction in Area	0.0	σ_a	59,600	psi
% Elongation	5.5	σ_t	59,400	psi
Type Failure	Shear	σ_r	1,310	psi
Failure Temp. °F	-16.3	$\bar{\sigma}_a$	63,200	psi
n	1.0	$\bar{\sigma}_t$	66,700	psi
m	0.945	$\bar{\sigma}_r$	1,310	psi
		τ_n	30,000	psi

REMARKS:

* Diameter obtained from girth of specimen after failure.

PIPE NO. 35 TEST NO. 33 AMBIENT TEMP 74 °F STRESS RATIO 3:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.057	0.055	0.054	0.037
	90°	0.056	0.055	0.054	0.039
	180°	0.056	0.055	0.054	0.034
	270°	0.056	0.055	0.054	0.041
O.D.	0°-180°	2.746	2.745	2.744	2.655
	90°-270°	2.745	2.744	2.744	2.655

	INITIAL	FINAL
Avg. I.D.	2.635	2.578
Avg. t	0.055	0.0385
L	2.0	2.484
Area	0.465	0.316

TEST DATA

TENSION lbs	HYD. PRESS. lbs
8160	3000
10880	4000
13600	5000
16320	6000
19040	7000
21760	8000
24480	9000
27200	10000
29900	11000
BREAK DATA	
28250	10500

TIME	mv	TEMP °F
0	-0.03	74
30	-1.40	
50	-2.00	
65	-2.00	
75	-2.05	
Break	-1.65	-2.6

TEST RESULTS AT FAILURE

% Reduction in Area	32	σ_a	72,800	psi
% Elongation	24.2	σ_t	24,450	psi
Type Failure	Shear	σ_r	510	psi
Failure Temp. °F	-2.6	$\bar{\sigma}_a$	106,300	psi
n	2.98	$\bar{\sigma}_t$	34,200	psi
$\bar{n}$	3.10	$\bar{\sigma}_r$	510	psi
		$\bar{\tau}_n$	43,800	psi

REMARKS:

PIPE NO. 36 TEST NO. 34 AMBIENT TEMP 70 °F STRESS RATIO 3:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.063	0.064	0.064	0.056
	90°	0.063	0.064	0.064	0.056
	180°	0.064	0.065	0.065	0.061*
	270°	0.064	0.064	0.065	0.056
O.D.	0°-180°	2.737	2.737	2.738	2.702
	90°-270°	2.736	2.736	2.737	2.702

	INITIAL	FINAL
Avg. I.D.	2.609	2.590
Avg. t	0.064	0.056
L	2.0	2.468
Area	0.537	0.465

TEST DATA

TENSION lbs	HYD. PRESS. lbs
13350	5000
16020	6000
18690	7000
21360	8000
24030	9000
26700	10000
29370	11000
32040	12000
34710	13000
BREAK DATA	
31900	13000

TIME	mv	TEMP °F
0	+0.01	70
50	-1.50	
60	-1.90	
70	-2.00	
90	-2.40	
110	-2.59	
120	-2.60	
Break	-2.42	-41.6

TEST RESULTS AT FAILURE

% Reduction in Area	13.4	σ_a	72,000	psi
% Elongation	23.4	σ_t	25,700	psi
Type Failure	Shear	σ_r	631	psi
Failure Temp. °F	-41.6	$\bar{\sigma}_a$	82,800	psi
n	2.80	$\bar{\sigma}_t$	29,200	psi
$\bar{n}$	2.83	$\bar{\sigma}_r$	631	psi
		$\bar{\tau}_n$	32,100	psi

REMARKS:

* Specimen did not fail at this point.

Specimen was unannealed.

PIPE NO. 37 TEST NO. 35 AMBIENT TEMP 70 °F STRESS RATIO 4:1

DIMENSIONS OF TEST SECTION

		INITIAL LEFT	INITIAL CENTER	INITIAL RIGHT	FINAL
t	0°	0.059	0.058	0.054	0.049
	90°	0.059	0.057	0.055	0.045
	180°	0.058	0.057	0.054	0.047
	270°	0.058	0.057	0.054	0.048
O.D.	0°-180°	2.766	2.764	2.762	2.684
	90°-270°	2.765	2.763	2.762	2.690

	INITIAL	FINAL
Avg. I.D.	2.649	2.593
Avg. t	0.057	0.047
L	2.0	2.118
Area	0.485	0.390

TEST DATA

TENSION lbs	HYD. PRESS. lbs
11080	3000
14765	4000
18450	5000
22135	6000
25820	7000
29505	8000
33200	9000
BREAK DATA	
33150	9000

TIME	mv	TEMP °F
0	+0.01	70
40	-1.70	
50	-2.00	
90	-2.35	
Break	-2.20	-35.5

TEST RESULTS AT FAILURE

% Reduction in Area	19.6	σ_a	78,300	psi
% Elongation	5.9	σ_t	20,270	psi
Type Failure	Shear	σ_r	437	psi
Failure Temp. °F	-35.5	$\bar{\sigma}_a$	96,900	psi
n	3.86	$\bar{\sigma}_t$	24,100	psi
$\bar{n}$	4.01	$\bar{\sigma}_r$	437	psi
		$\bar{\tau}_n$	41,200	psi

REMARKS:

Specimen was unannealed.

COMPARATIVE DATA   Stress Ratio Around 1

Test No.	$\bar{n}$	$\bar{\sigma}_a$ Psi	$\bar{\sigma}_t$ Psi	Temp. ^oF	Type Fail.	t init. In.	Var. in init. t %	Var. in final t %	Elong. %	Red. Area %	Heat Treat.	Finish Outside	Finish Inside	Dist. of failure from end of test sect. In.
23	0.93	69,100	74,500	-2.2	Shear	0.053	3.2	2.2	12.5	0.5	YES	Smooth	Very Rough	Right-2
27	0.86	81,100	94,400	-8.5	Shear	0.052	2.0	13.9	18.7	8.8	YES	Smooth	Fairly Rough	Right-1.4
32	0.94	63,200	66,700	-16.5	Shear	0.058	1.8	3.7	5.5	0	YES	Smooth	Fairly Smooth	Right-1.875
28	0.94	69,700	74,000	-23.3	Shear	0.055	1.9	0	6.2	0	Yes	Smooth	Fairly Smooth	2
31	0.89	82,000	92,400	-36.7	Shear	0.056	9.3	14.3	17.1	7.7	No	Smooth	Smooth	2
5	1.39	104,100	75,300	-48.0	Shear	0.058	3.5	24.4	12.1	24.2	Yes	Smooth	Smooth	Left-0.125

COMPARATIVE DATA   Stress Ratio Around 2

Test No.	$\bar{n}$	$\bar{\sigma}_a$ Psi	$\bar{\sigma}_t$ Psi	Temp. °F	Type Fail.	t init. In.	Var. in init. t %	Var. in final t %	Elong. %	Red. Area %	Heat Treat.	Finish Outside	Finish Inside	Dist. of failure from end of test sect. In.
20	2.07	94,900	45,700	-1.0	Shear	0.067	3.2	2	14.8	24.4	Yes	Smooth	Fairly Smooth	Left-0.5
15	2.05	84,100	41,100	-18.3	Shear	0.070	4.3	3.6	17.9	18.6	Yes	Smooth	Very Rough	Left-2
11	2.14	93,000	43,400	-28	Shear	0.074	1.4	6.7	16.5	17	Yes	Smooth	Smooth	Right-0.5
14	1.92	92,600	48,100	-28.2	Shear	0.077	1.3	4.9	25.8	19.2	Yes	Smooth	Smooth	Right-1.875
25	2.0	75,200	37,600	-37	Shear	0.052	3.9	6.7	10.9	10.4	Yes	Smooth	Fairly Smooth	Right-0.125
1	1.92	73,700	38,400	-39	Shear	0.055	13.7	27.9	8.6	9.2	Yes	Rough	Rough	Left-0.25
16	2.17	90,600	41,600	-40.7	Shear	0.074	5.6	1.6	10.1	17.6	Yes	Smooth	Fairly Smooth	Right-0.875
22	2.0	103,000	51,600	-42.3	60% Cleavage	0.062	10.2	12.8	14.8	19.3	No	Smooth	Rough	Right-0.25
29	1.96	83,800	42,700	-50	Shear	0.051	8.7	7.7	7.8	21.6	Yes	Smooth	Rough	Left-0.5

COMPARATIVE DATA   Stress Ratio Around 3

Test No.	$\bar{n}$	$\bar{\sigma}_a$ Psi	$\bar{\sigma}_t$ Psi	Temp. °F.	Type Fail.	t init. In.	Var. in init. t %	Var. in final t %	Elong. %	Red. Area %	Heat Treat.	Finish Outside	Finish Inside	Dist. of failure from end of test sect. In.
30	3.15	84,800	26,850	0	Shear	0.064	1.6	11.8	14.8	18.2	Yes	Smooth	Fairly Rough	Right-0.2
33	3.1	106,300	34,200	-2.6	Shear	0.055	1.8	29.4	24.2	32	Yes	Smooth	Smooth	2
13	2.94	87,200	29,650	-3.0	Shear	0.079	1.3	10.3	15.6	25.5	Yes	Smooth	Fairly Rough	Right-0.25
26	3.2	74,400	23,250	-17.2	Shear	0.050	2.0	15	20.3	16.9	Yes	Smooth	Rough	Left-1.25
18	3.2	96,100	30,000	-23.3	Shear	0.078	2.6	6.6	20.3	26.2	Yes	Smooth	Smooth	Left-0.375
6	2.9	112,500	38,700	-26.9	5% Cleavage	0.066	1.6	4.9	17.2	36.4	Yes	Smooth	Fairly Rough	Left-0.875
21	3.1	97,500	31,400	-34.5	Shear	0.076	8.1	5.2	20.3	20	Yes	Smooth	Smooth	Left-0.6
34	2.83	82,800	29,200	-41.6	Shear	0.064	1.6	8.9	23.4	13.4	No	Smooth	Fairly Rough	Left-0.3
2	3.08	101,000	31,750	-44.8	Shear	0.074	5.4	7.1	29.5	27.6	Yes	Smooth	Smooth	Right-1.5

COMPARATIVE DATA   Stress Ratio Around 4

Test No.	$\bar{n}$	$\bar{\sigma}_a$ Psi	$\bar{\sigma}_t$ Psi	Temp. °F	Type Fail.	t init. In.	Var. in init. t %	Var. in final t %	Elong. %	Red. Area %	Heat Treat.	Finish		Dist. of failure from end of test sect. In.
												Outside	Inside	
4	4.4	107,800	24,500	1.1	Shear	0.083	5	3.3	25.4	33.6	Yes	Smooth	Smooth	Left-1.875
17	4.42	93,000	21,000	-8.3	Shear	0.076	2.7	5.3	35.9	25.8	Yes	Smooth	Rough	Right-0.375
7	4.28	85,100	19,850	-25.7	55% Cleavage	0.087	2.3	9	25	23.1	Yes	Smooth	Discontinuity	0.25
3	13.5	109,000	8,060	-29.4	Shear	0.103	6.1	14.9	25	36.5	Yes	Smooth	Smooth	Left-1
10	4.55	103,800	22,800	-34.2	Shear	0.095	2.1	3	24.2	33.8	Yes	Smooth	Rough	Left-0.875
9	4.34	86,100	19,870	-35.4	Shear	0.066	6.2	7.7	30.3	21.3	Yes	Smooth	Smooth	0.875
35	4.01	96,100	24,100	-35.5	Shear	0.057	1.8	8.9	5.9	19.6	No	Smooth	Fairly Smooth	Right-0.5
19	4.56	113,500	24,850	-43.1	Shear	0.083	1.2	1.7	36	33.2	Yes	Smooth	Smooth	2
12	4.56	97,900	21,400	-50.6	Shear	0.088	2.3	6.1	15.6	26.4	Yes	Smooth	Rough	Left-0.125

APPENDIX II

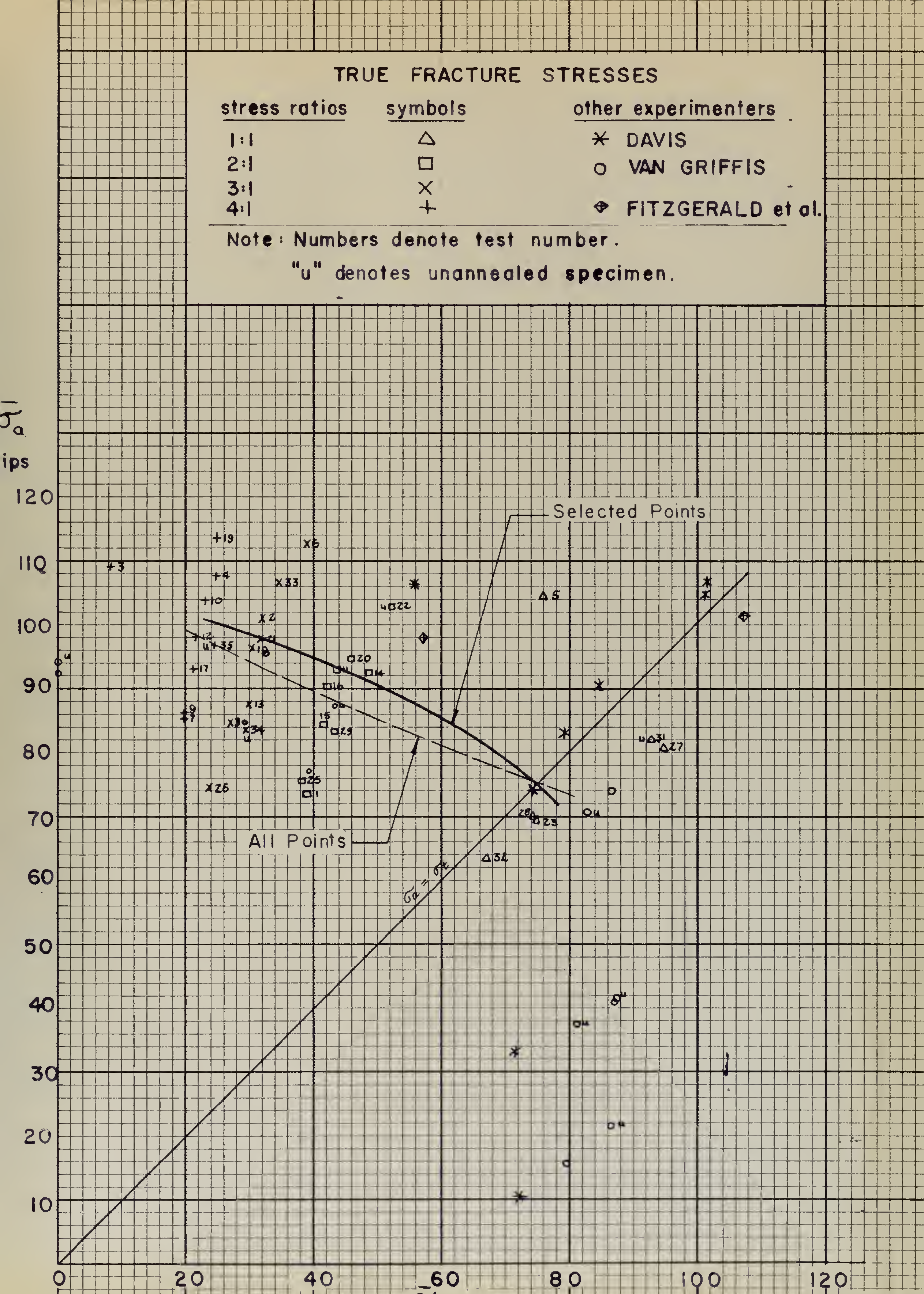
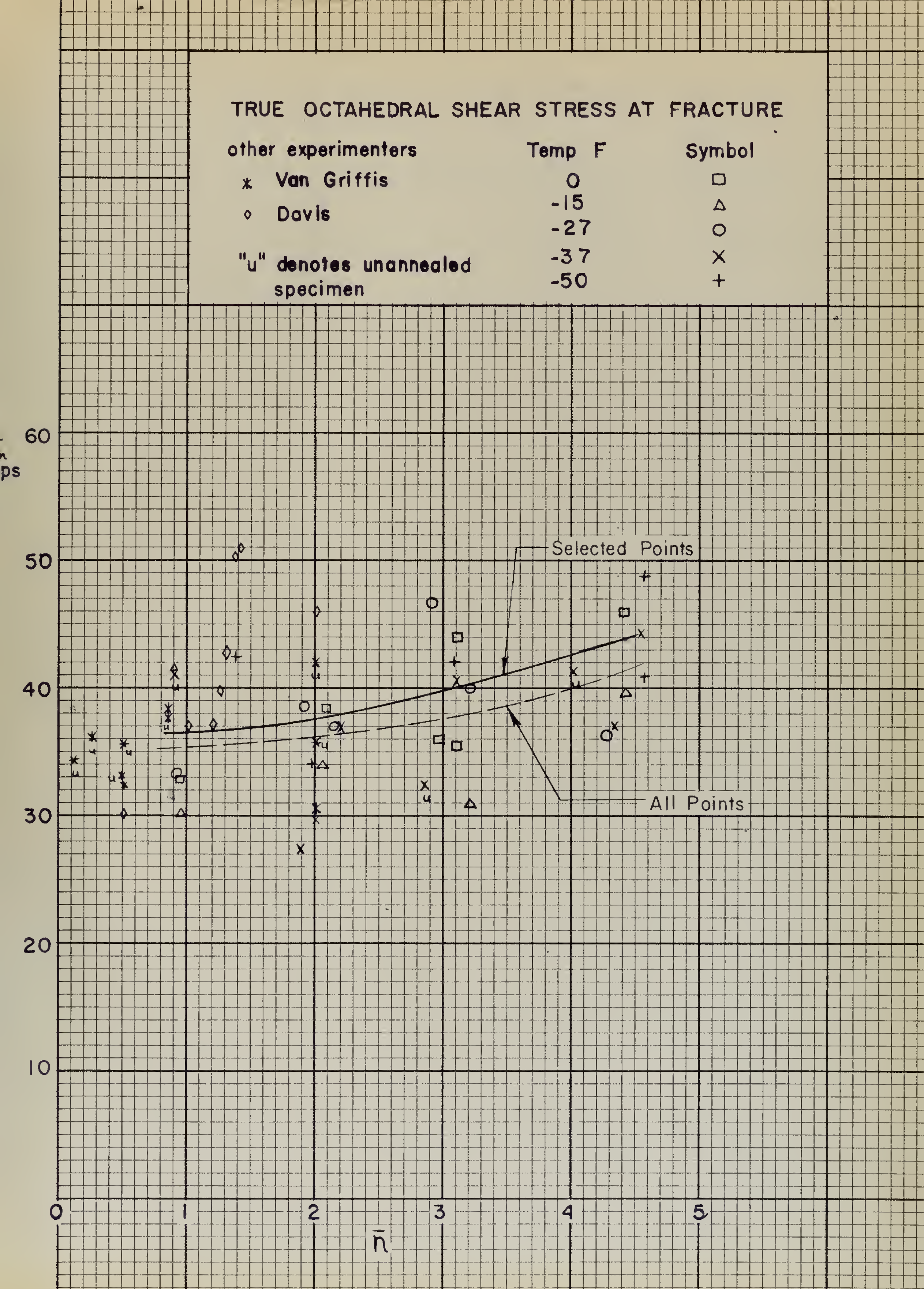

TRUE FRACTURE STRESSES
stress ratios
symbols
other experimenters
1:1
2:1
3:1
4:1
DAVIS
VAN GRIFFIS
FITZGERALD et al.
Note: Numbers denote test number.
"u" denotes unannealed specimen.
Selected Points
All Points
$\bar{\sigma}_a = \bar{\sigma}_t$
$\bar{\sigma}_a$
kips
$\bar{\sigma}_t$ kips
0
20
40
60
80
100
120
10
20
30
40
50
60
70
80
90
100
110
120

Plate 39



TRUE OCTAHEDRAL SHEAR STRESS AT FRACTURE
other experimenters
Temp F
Symbol
Van Griffis
Davis
"u" denotes unannealed specimen
0
-15
-27
-37
-50
Selected Points
All Points
ps
60
50
40
30
20
10
0
1
2
3
4
5
n̄

Plate 40

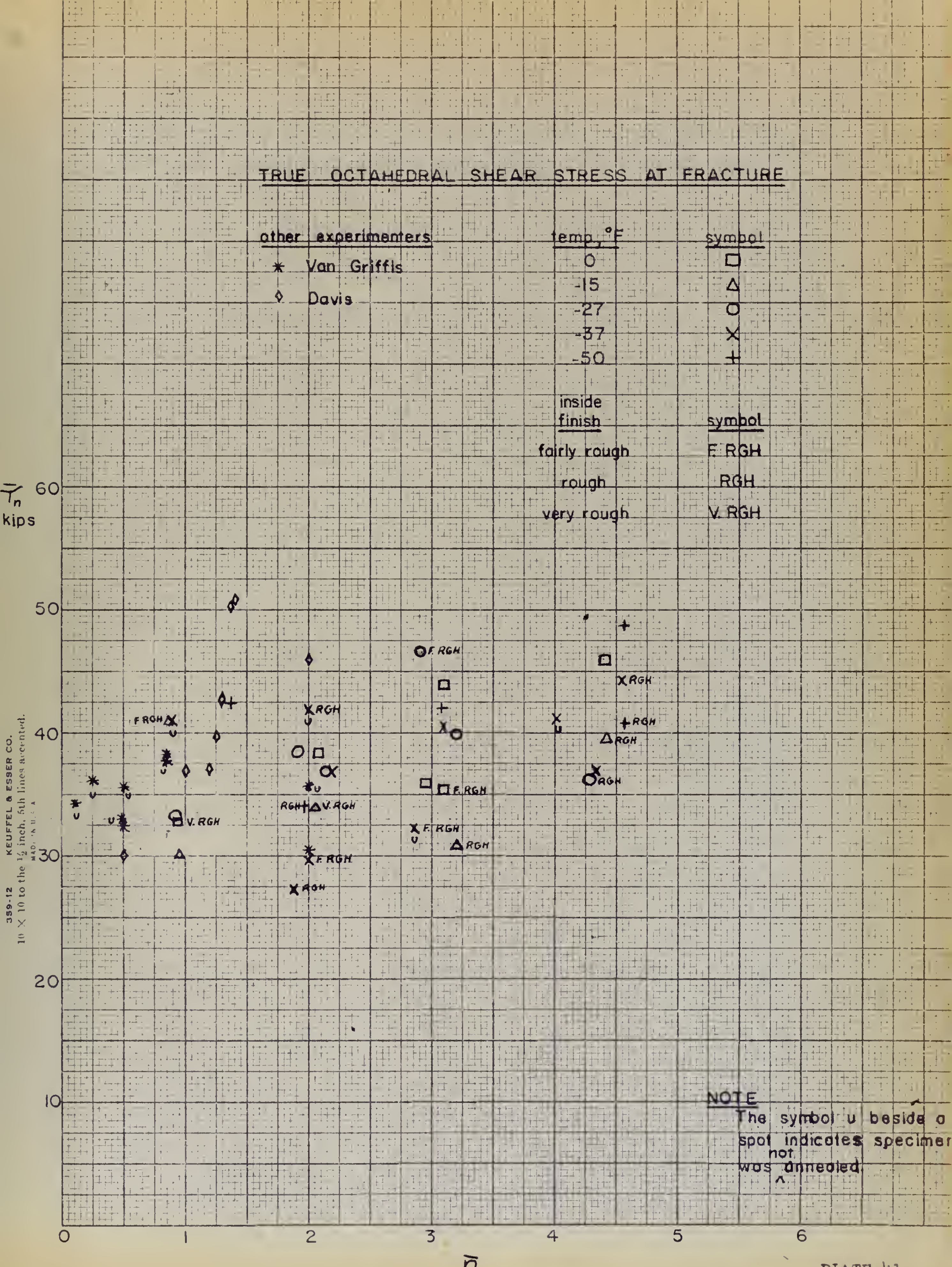
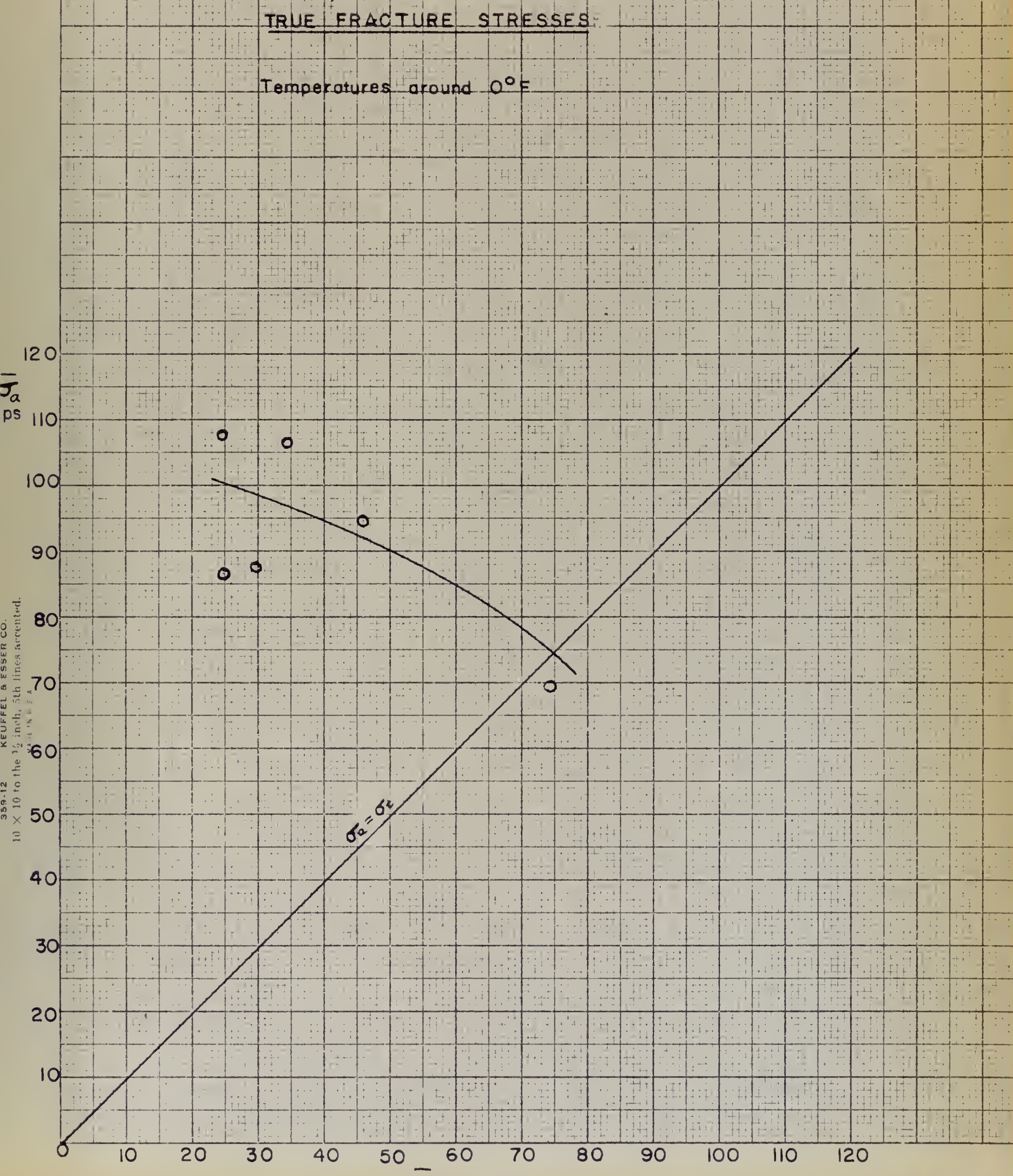

TRUE OCTAHEDRAL SHEAR STRESS AT FRACTURE
other experimenters
Van Griffis
Davis
temp, °F
0
-15
-27
-37
-50
symbol
inside finish
fairly rough
rough
very rough
F. RGH
RGH
V. RGH
NOTE
The symbol u beside a spot indicates specimen was not annealed.
$\bar{\tau}_n$ kips
$\bar{n}$
10
20
30
40
50
60
0
1
2
3
4
5
6

PLATE 41



TRUE FRACTURE STRESSES
Temperatures around 0°F
$\overline{\sigma}_a$
ps
120
110
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
110
120
$\overline{\sigma}_a = \overline{\sigma}_t$
$\overline{\sigma}_t$, kips

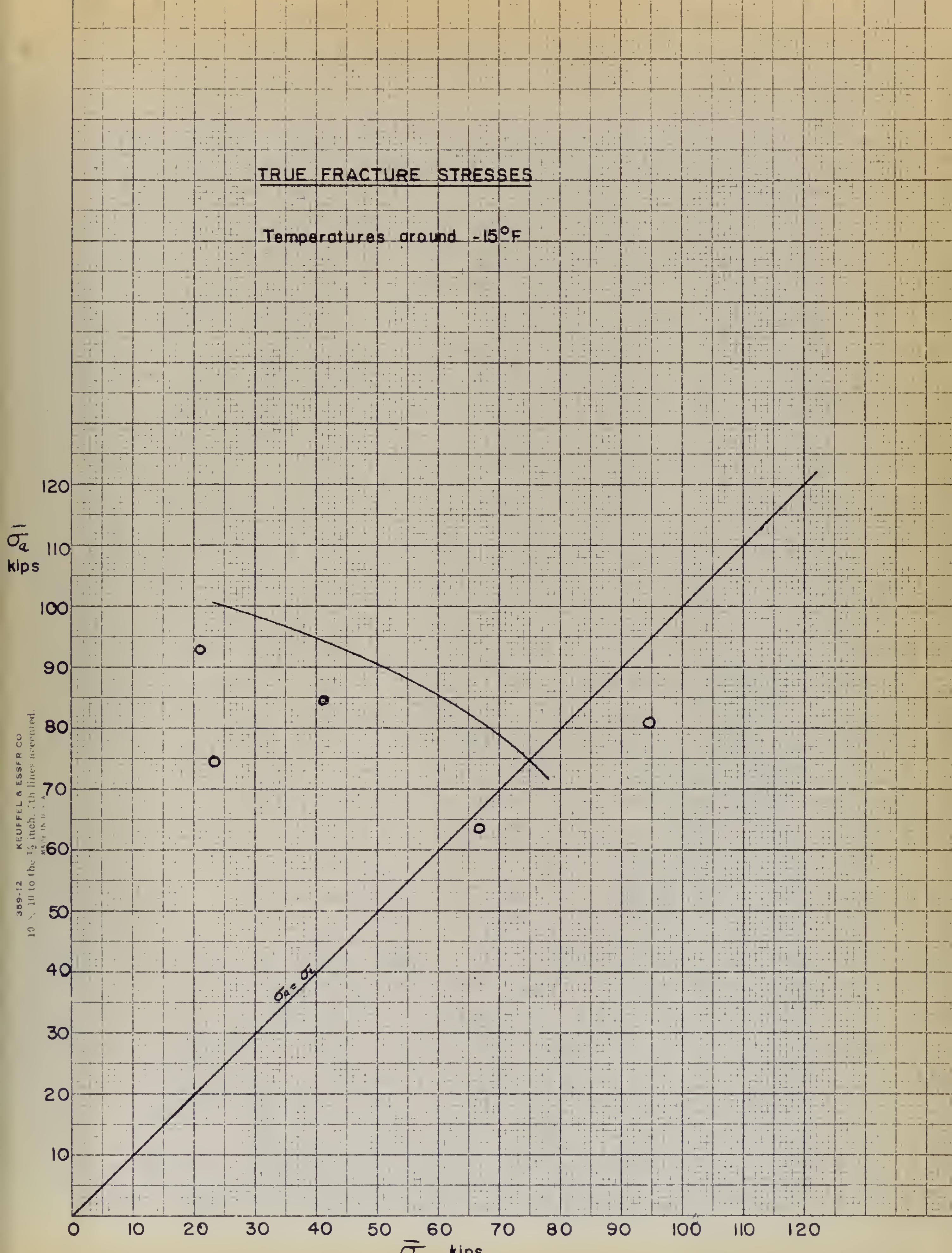
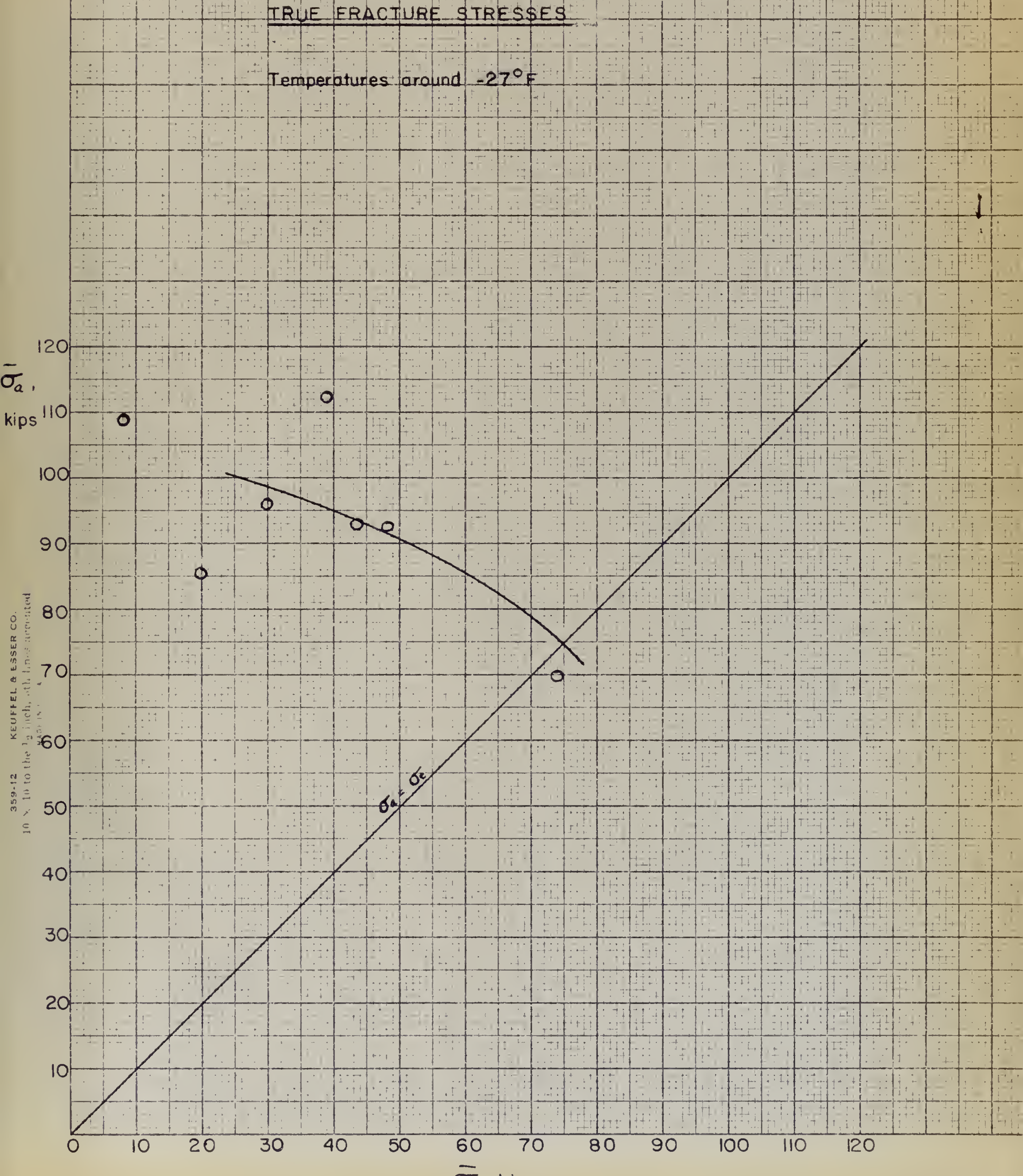
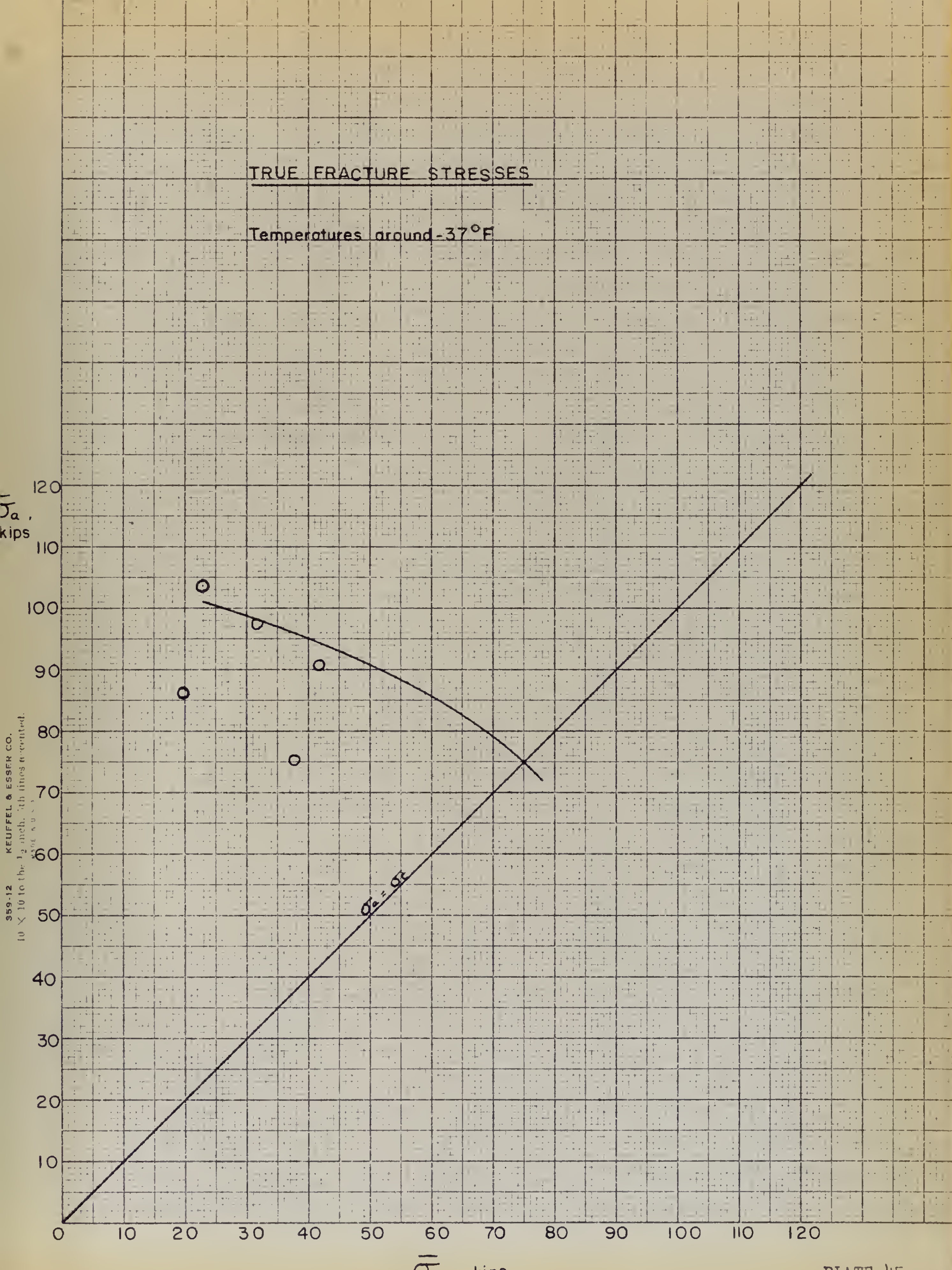

TRUE FRACTURE STRESSES
Temperatures around -15°F
$\overline{\sigma_a}$ kips
$\overline{\sigma_t}$, kips
$\sigma_a = \sigma_t$
0
10
20
30
40
50
60
70
80
90
100
110
120

PLATE 43



TRUE FRACTURE STRESSES
Temperatures around -27°F
σ_a', kips
$\sigma_a = \sigma_t$
$\bar{\sigma}_t$, kips
0
10
20
30
40
50
60
70
80
90
100
110
120
359-12 KEUFFEL & ESSER CO.



TRUE FRACTURE STRESSES
Temperatures around -37°F
$\overline{\sigma_a}$, kips
$\overline{\sigma_t}$, kips
$\sigma_a = \sigma_t$
0
10
20
30
40
50
60
70
80
90
100
110
120
359-12 KEUFFEL & ESSER CO.

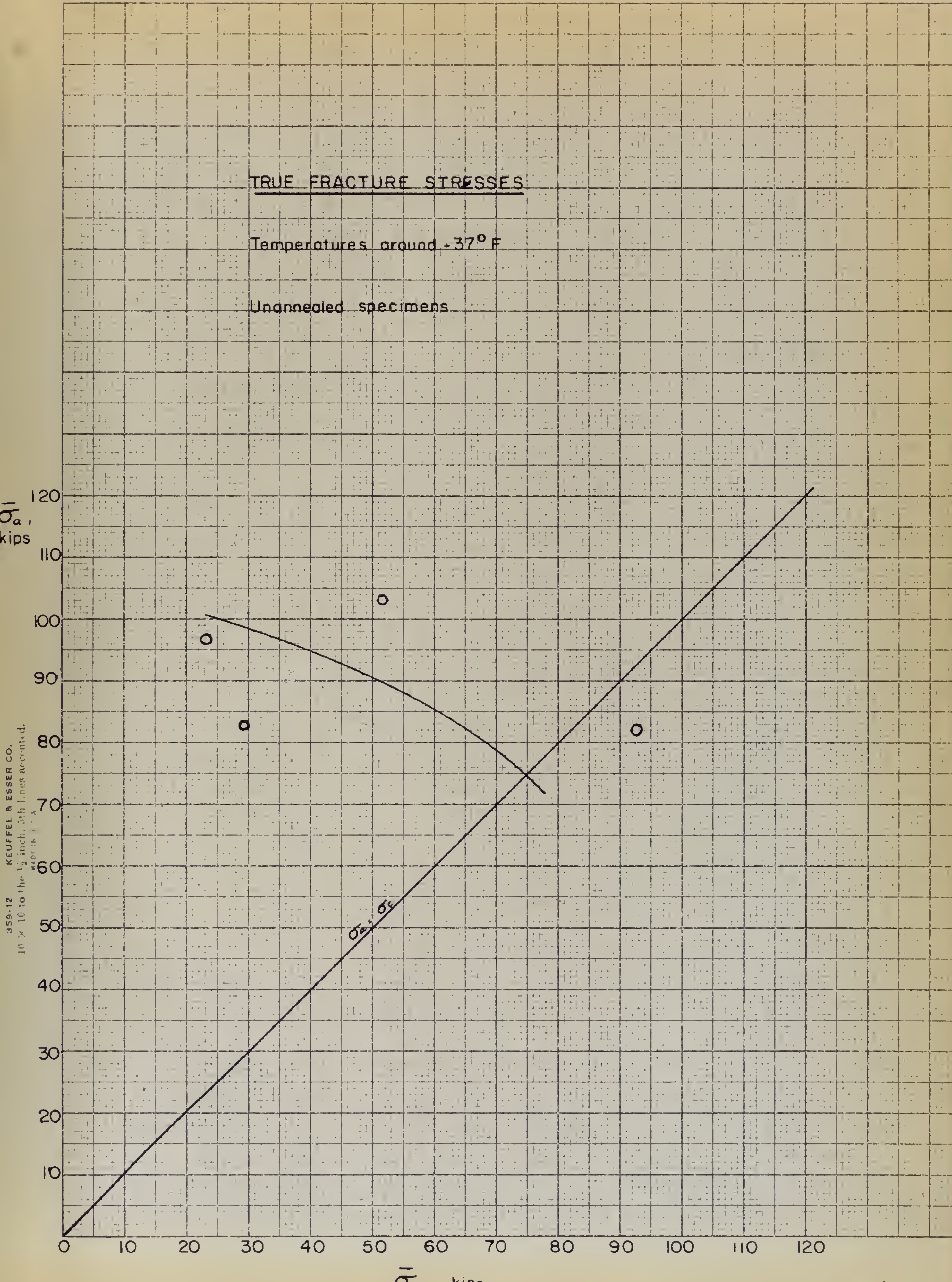
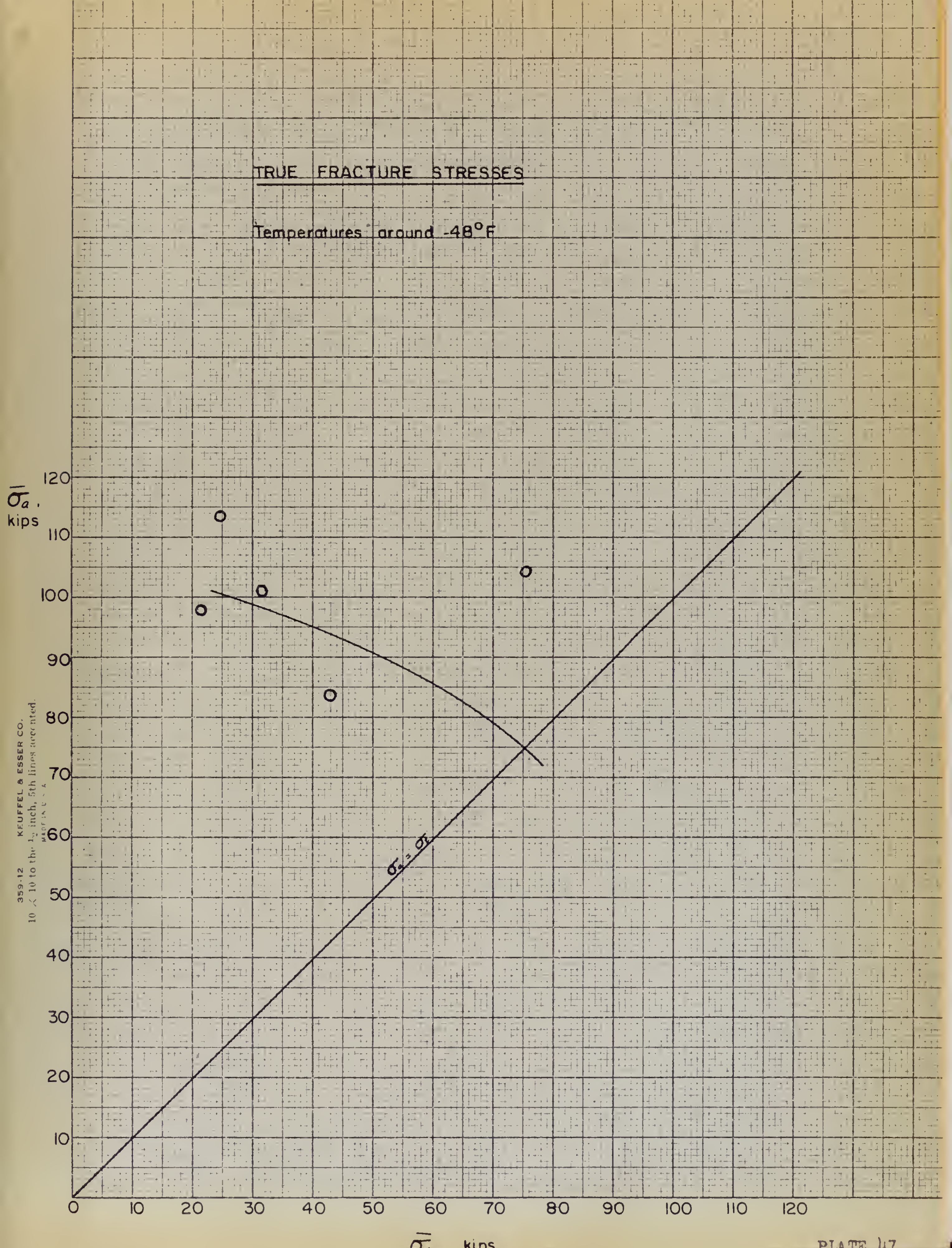
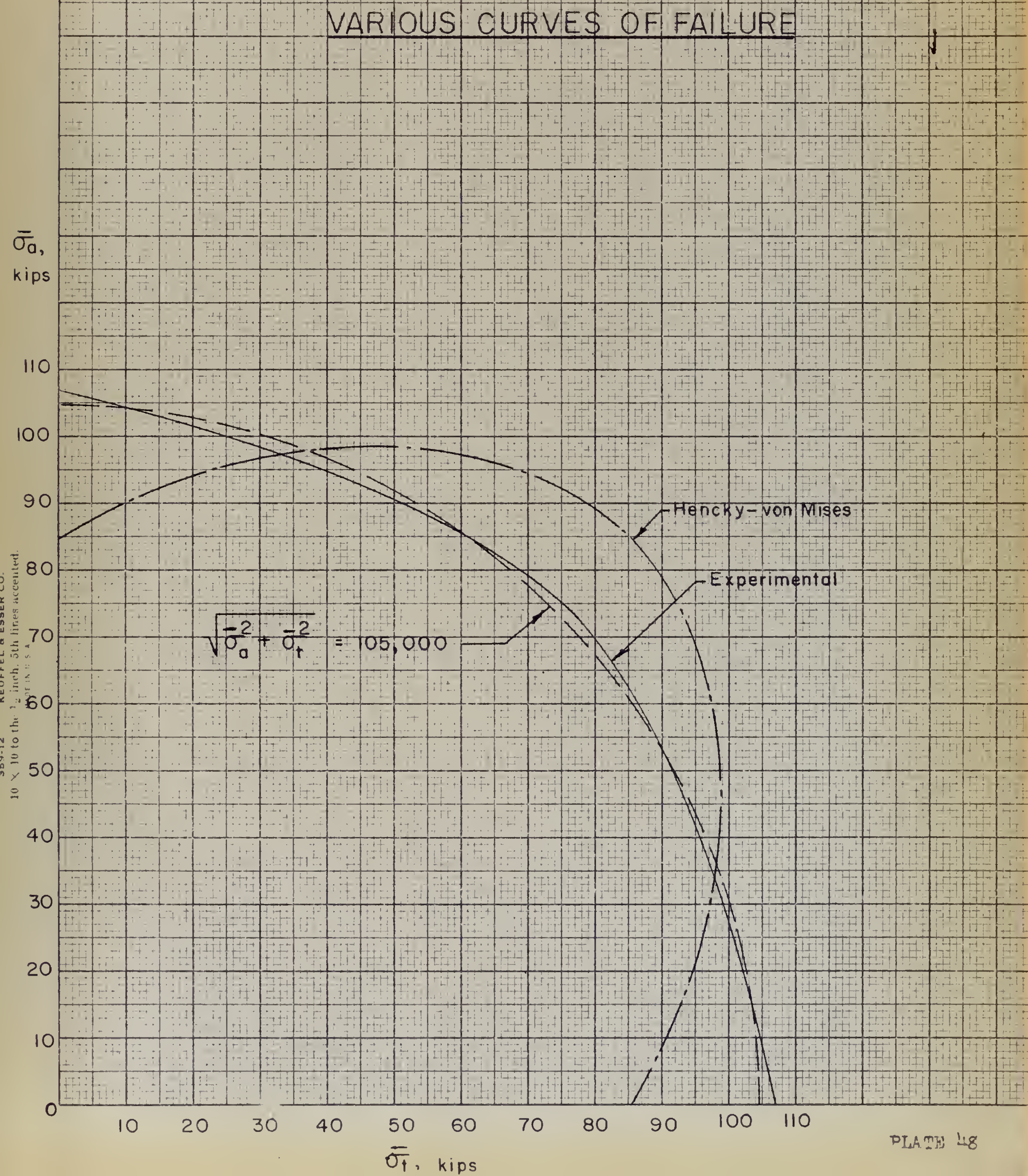

TRUE FRACTURE STRESSES
Temperatures around -37° F
Unannealed specimens
$\bar{\sigma}_a$, kips
$\bar{\sigma}_t$, kips
$\sigma_a = \sigma_t$
0
10
20
30
40
50
60
70
80
90
100
110
120
KEUFFEL & ESSER CO.
359-12

PLATE 46



TRUE FRACTURE STRESSES
Temperatures around -48°F
$\overline{\sigma}_a$, kips
$\overline{\sigma}_t$ kips
$\sigma_a = \sigma_t$
0
10
20
30
40
50
60
70
80
90
100
110
120
359-12 KEUFFEL & ESSER CO.
10 X 10 to the 1/2 inch, 5th lines accented.



VARIOUS CURVES OF FAILURE
$\bar{\sigma}_a$, kips
$\bar{\sigma}_t$, kips
0
10
20
30
40
50
60
70
80
90
100
110
Hencky-von Mises
Experimental
$\sqrt{\bar{\sigma}_a^2 + \bar{\sigma}_t^2} = 105,000$

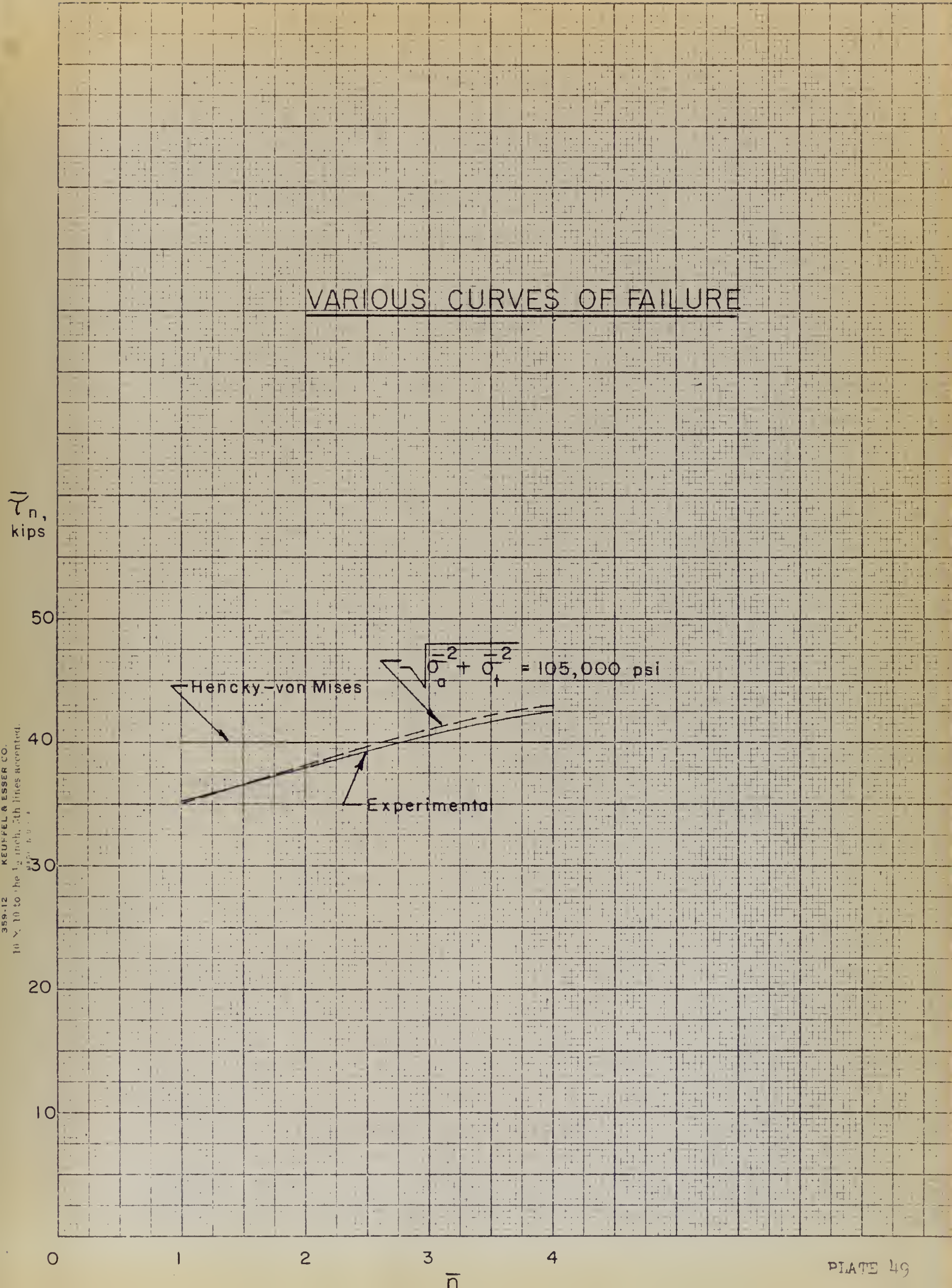

VARIOUS CURVES OF FAILURE
τ_n, kips
50
40
30
20
10
0
1
2
3
4
$\bar{n}$
Hencky-von Mises
$\sqrt{\bar{\sigma}_a^2 + \bar{\sigma}_t^2} = 105{,}000$ psi
Experimental
359-12 KEUFFEL & ESSER CO.

PLATE 49

APPENDIX III

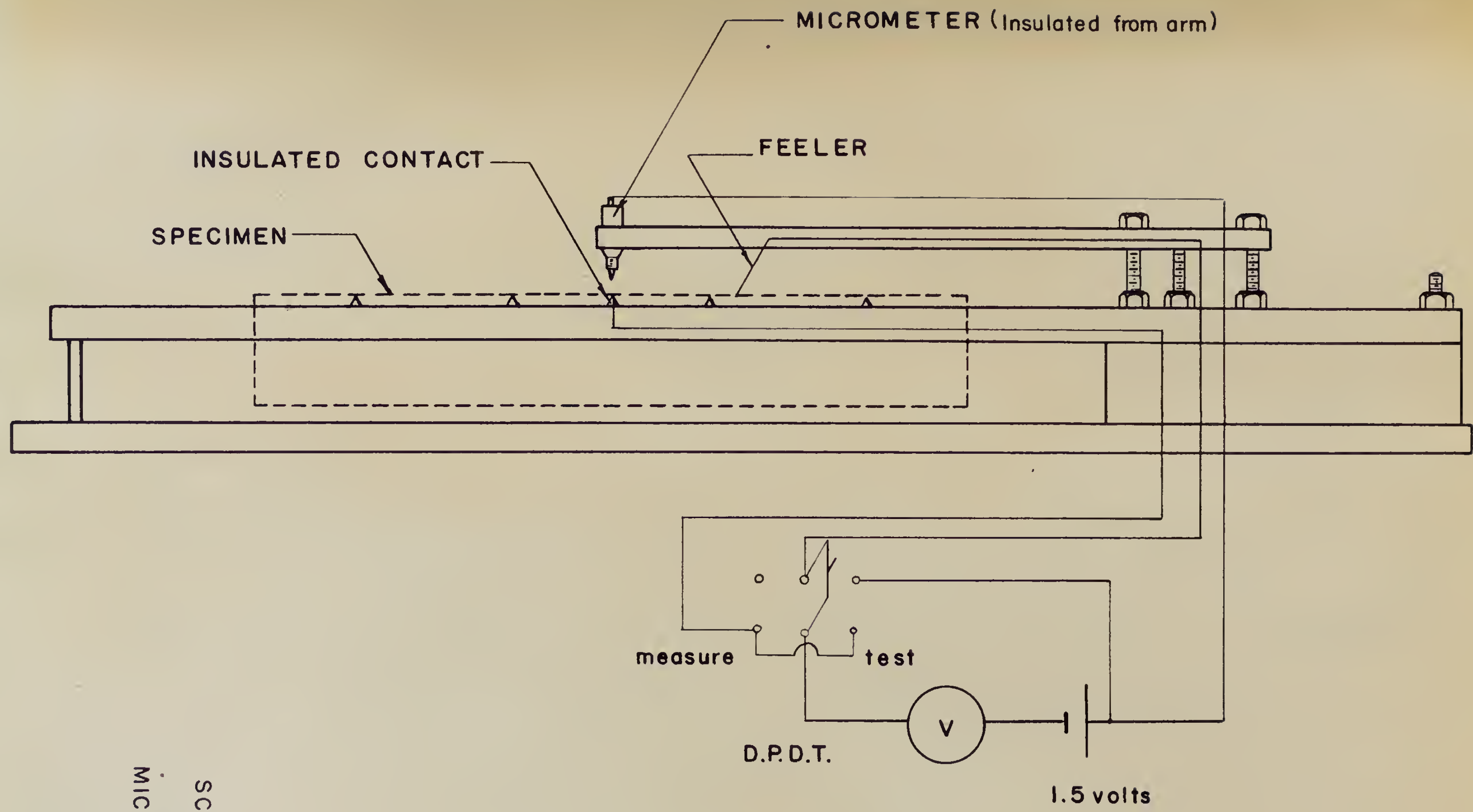
FORMULAE

$$\sigma_a = \frac{\frac{4P}{\pi} + \frac{ID^2 \times p}{10.29}}{4t(ID + t)}$$

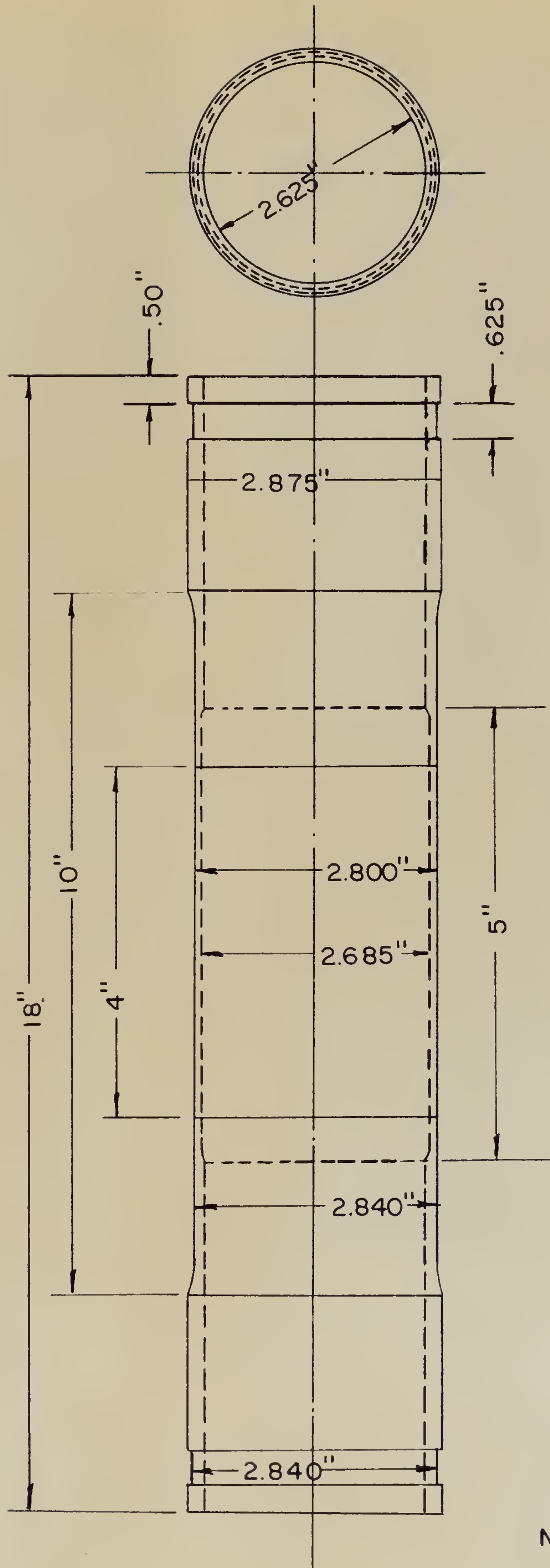
$$\sigma_t = \frac{p \times ID}{20.58t}$$

$$\sigma_r = \frac{p}{20.58}$$

$$\bar{\tau}_n = \frac{1}{3}\sqrt{(\bar{\sigma}_a - \bar{\sigma}_t)^2 + (\bar{\sigma}_a - \bar{\sigma}_r)^2 + (\bar{\sigma}_t - \bar{\sigma}_r)^2}$$



SCHEMATIC
OF
MICROMETER



Not to scale

TYPICAL SPECIMEN

Note: O.D. & I.D. of 4" Test Section depend on wall thickness desired.

Bibliography

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(7) " Yielding and Fracture of Medium-Carbon Steel Under Combined Stress", by E. A Davis, Journal of Applied Mechanics, March 1945.

24 NOV 70

17555

Thesis
R578 Risser 28855

A study of the effects of stress ratio and low temperature on the failure of mild steel cylinders.

24 NOV 70

17555

Thesis
R578 Risser 28355

A study of the effects of stress ratio and low tempera-ture on the failure of mild steel cylinders.